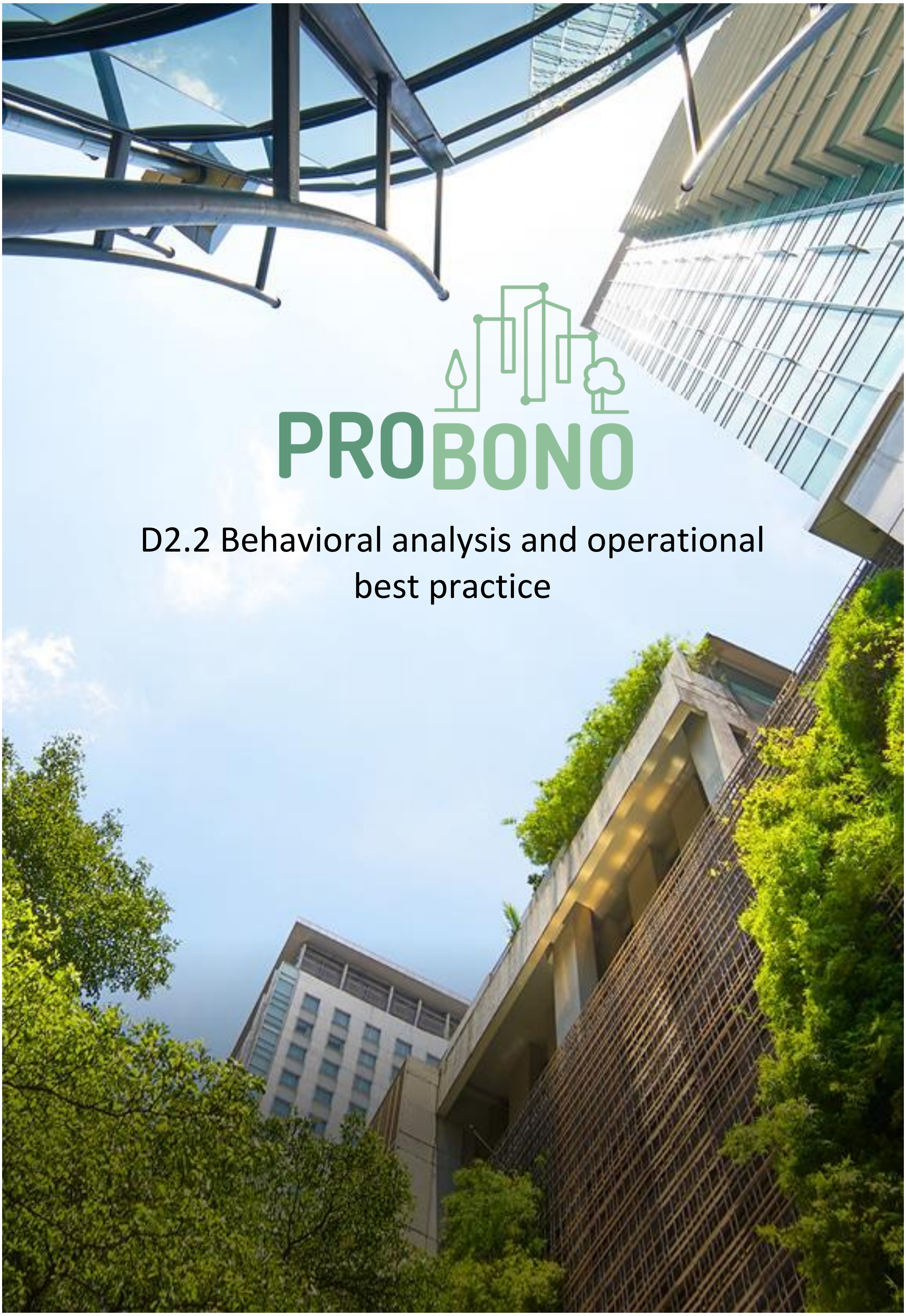


PROBONO

D2.2 Behavioral analysis and operational best practice

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101037075. This output reflects only the author's view, and the European Union cannot be held responsible for any use that may be made of the information contained therein.

The Integrator-centric approach for realising innovative energy efficient buildings in connected sustainable green neighbourhoods

Deliverable nº:	**D2.2**
Deliverable name:	**Behavioural analysis and operational best practice**
Version:	**0.4**
Release date:	**28.12.2022**
Dissemination level:	**Public**
Status:	**Peer-reviewed**
Author:	**EUR - Darren McCauley**

Document history:

Version	Date of issue	Content and changes	Edited by
0.1	21/10/2022	Pre-First draft version 50%	Darren McCauley
0.2	31/10/2022	First draft version 50%	Darren McCauley
0.3	30/11/2022	First draft version 100%	Darren McCauley
0.4	15/12/2011	Post-QA, post-review	Darren McCauley

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101037075. This output reflects only the author's view, and the European Union cannot be held responsible for any use that may be made of the information contained therein.

Contributors:

Partner	Contributor
EUR	Darren McCauley
EUR	Kerry Pettigrew
EUR	Inge Meems
EUR	Victoria Unverzagt
EUR	Ryan Holmes

Peer reviewed by:

Partner	Reviewer
VISB	Marta Boaventura
CELSA	Oscar Carreras Gallo

Deliverable beneficiaries:

WP / Task
WP2/T2.2

DEFINITIONS[1]

A Green Building (GB) (new or retrofit) is a building that, in its design, construction and operation, reduces or eliminates negative impacts, and can create positive impacts, on the climate, social, and natural environment. GBs preserve precious natural resources and improve quality of life[2]. Specifically, this means that GBs should be very energy efficient, use extensively the potential of locally available renewable energy, use sustainable materials, and aim for a low environmental impact over the entire life cycle. GBs offer their users and residents a healthy climate and a high quality of stay, they are resilient e.g., to environmental change and contribute to social inclusion.

[1] Please refer to the last submitted reports for the latest status of the definitions

[2] https://www.worldgbc.org/what-green-building

Green Neighbourhoods aligned with the European Green Deal[3], is a set of buildings over a delimited area, at a scale that is smaller than a district, with potential synergies, in particular in the area of energy. A green neighbourhood is a neighbourhood that allows for environmentally friendly, sustainable patterns and behaviours to flourish e.g., bioclimatic architecture, renewable energy, soft and zero-emission mobility etc. Green neighbourhoods are the building blocks of Positive Energy Districts (PEDs)[4] by implementing key elements of PED energy systems. For example, the exchange of energy between buildings increases the share of local self-supply with climate-neutral energy and system efficiency. They also provide the technical conditions to enable Citizen Energy Communities[5] and Renewable Energy Communities[6] to be implemented.

Green Buildings and Neighbourhoods (GBN) in PROBONO are GBs integrated at delimited area or district level with green energy and green mobility management and appropriate infrastructure supported by policies, investments and stakeholders' engagement and behaviours that ensures just transition that maximise the economic and social cobenefits considering a district profile (population size, socio-economic structure, and geographical and climate characteristics). Delivered in the right way, GBN infrastructure is a key enabler of inclusive growth, can improve the accessibility of housing and amenities, reduce poverty and inequality, widen access to jobs and education, make communities more resilient to climate change, and promote public health and wellbeing.

DGNB certification serves as a quality stamp ensuring the state of the building for buyers. The Green Building Council Denmark (2010) established the German certification DGNB meaning 'German Society for Sustainable Buildings'. The Danish version of DGNB was created to obtain a common definition of what sustainability is towards and making it measurable. A consortium of experts was established from all parts of the construction sector. DGNB had to be reshaped for the Danish standards, practice, traditions, and laws but is now available to certify any construction project. They chose DGNB as an innovation-forward and sustainable future guarantee. DGNB diversifies itself by focusing on sustainability and not just the environment. DGNB creates a standardised framework for the construction operations conditions and creates a common language which facilitates communication between professions and helps organize and prioritize the efforts in long and complicated development phases.

Life cycle assessment (LCA)[7] is a tool used for the systematic quantitative assessment of each material used, energy flows and environmental impacts of products or processes. LCA assesses various aspects associated with development of a product and its potential impact throughout a product's life (i.e., cradle to grave) from raw material acquisition, processing, manufacturing, use and finally its disposal. In PROBONO, LCA represents the statement of a building's total energy, resource consumption and environmental impact in the manufacture, transport, and replacement of materials and for its operation over its expected life. Social life cycle assessment (S-LCA)[8] is a method to assess the social and sociological aspects of products, their actual and potential positive as well as negative impacts along the life cycle. Life-cycle costing (LCC)[9] considers all the costs incurred during the lifetime of the product, work, or service.

[3] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[4] SET-Plan Action 3.2: https://jpi-urbaneurope.eu/wp-content/uploads/2021/10/setplan_smartcities_implementationplan-2.pdf

[5] Internal Electricity Market Directive (EU) 2019/944

[6] Renewable Energy Directive II (EU) 2018/2001

[7] https://op.europa.eu/en/publication-detail/-/publication/16cd2d1d-2216-11e8-ac73-01aa75ed71a1/language-en

[8] https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/social-lca/

[9] https://ec.europa.eu/environment/gpp/lcc.htm

Table of Contents

Table of Figures

List of tables

Abbreviations and Acronyms

Acronym	Description
A/C	Air conditioning
EU	European Union
HVAC	Heating ventilation and air conditioning
LL	Living lab
PCS	Personal comfort systems
UAE	United Arab Emirates
UK	United Kingdom
USA	United States of America
WSN	Wireless sensor network

Executive summary

The goal of this investigation was to conduct a review of the academic research published in the last five years which discusses or evaluates the energy-related behaviours of building occupants. We aimed to determine the main topics that have attracted academic attention, as well as the research methods used, and the context in which research has been conducted. This includes the location of the study, the type of building being scrutinised, and the type of occupant referred to – for example, a particular age group, or occupational group. The most robust method for this goal is a systematic review, whereby bibliographic database(s) are searched for publications matching predetermined criteria, and these publications reviewed for a specific set of observations. We aim ultimately to offer insights into each building type present in the living labs, and thus offering a database for investigating where carbon footprint behaviours are likely to be most prevalent and targetable for future research in Probono, based on a systematic interrogation of existing research from the past five years.

1. Introduction

1.1 Deliverable overview and report structure

Deliverable D2.2 requires an analysis of carbon footprint behaviours, aiming to classify the key behaviours and provide a basis for best practice guidelines to be used by the living labs in their design of operations. Emphasis is put on behaviours, and analysis is to be conducted drawing on information derived from data from real operations or simulations of real-life scenarios. These key behaviour classifications are to be tailored as closely as possible to the living labs, to inform the design of best practice initiatives to optimally reduce energy usage through modifying occupant behaviour. Known and emerging trends are to be identified, to facilitate the creation of clear guidelines for the long-term sustainability of buildings. Mitigation measures and incentive models are to be identified, using quantitative and qualitative methods, involving key stakeholders, and providing input to other relevant work packages.

We obtained the necessary information by looking to the wealth of published research studies available over the last five years, both quantitative and qualitative, investigating the impact of occupants' carbon footprint behaviours in a broad range of building types using real-life scenarios or their simulations. This approach offered a realistic and comprehensive methodology for covering all aspects of Task 2.2, including ST2.2.1-2.2.3 (as outlined further in section 1.2 below). This report is structured as follows: firstly, an outline of the systematic review process undertaken, including a summary of the data sources, the search criteria, the data extracted and the methods of analysis. Initial findings from a pilot dataset are then described, giving a preliminary overview of behaviours and associated metadata, such as building type, occupant type (stakeholder) and the type of methods and data used in the study (qualitative or quantitative). These initial findings are expanded to describe the complete dataset as it currently stands (approximately 600 research articles spanning 2018-2022), enabling a full analysis of occupant/stakeholder behaviours in a range of building types and locations. We describe a statistical analysis identifying behaviours specific to individual living labs, as well as a descriptive analysis of research conducted on buildings within the country or, where available, the city where each living lab is located. We conclude with a summary of the key findings, and recommendations as well as plans for ongoing augmentation of the database.

1.2 Mapping Probono outputs

In this section we identify which sections of the report specifically address each subtask and justify the rationale for our choice of strategy, as summarised in Table 1.

Subtask ST2.2.1 requires us to identify the behaviours that most impact on carbon footprint, based upon ground truth data through real operations or simulations of real-life scenarios. To address this subtask, we sought to utilise the insights made by a diverse range of experts in the field, from engineers to sociologists, in research published over the last five years. Over 600 research articles were included, many of which use data from real life operations or simulations. We selected research articles investigating energy-related carbon footprint behaviours in all building types, on a global scale, creating a detailed database which is openly accessible via the link provided in the Appendix. This analysis of behaviours, at varying levels of granularity, will inform stakeholder analyses, providing robust guidance into which behaviours are at the forefront of research activity, with details of building type and location, as well as the methods used to gather and analyse data.

This leads to subtask ST2.2.2, which seeks to elicit best practice initiatives at an organisation-, facility- and building-level. Using the metadata gathered during our data collection process (systematic review), we performed statistical analysis to determine building-type-specific behaviours, distinguishing them from more generic energy-related behaviours which are broadly relevant to all building types. We supplemented this statistical analysis with a descriptive summary of a subset of the dataset: research focusing on energy-related occupant behaviours in buildings located in the individual living labs' cities (where possible) or countries.

Finally, subtask ST2.2.3 focuses on mitigation measures and incentive models for stakeholders. It was firstly necessary to identify what groups of people feature among Probono stakeholders. Users can be key stakeholders, such as businesses or workers. For this, we surveyed the database for information on the type of building occupant under consideration in each research study. We identified this as a necessary addition to Task 2.1 which then focuses on the formal organisations involved in each living lab. We made sure not to overcomplicate the potential range of stakeholder groups to aid with overall analysis as set out in section 2. This also avoids repetition of insight that would be provided from Task 2.1. This information, which is described in detail the report, informs stakeholder interactions and analysis, with the more in-depth stakeholder analysis taking place in ST2.1.1. We also reflect on key recommendations for stakeholders in section 6.2.

GA Component Title	GA Component Outline	Respective Document Chapter(s)	Justification
TASKS			
Task 2.2 Behavioural analysis and operational best practice	**ST2.2.1 Behavioural Carbon Footprint Analysis** Identify the behaviours that most impact upon carbon footprint. Capture predicted interactions of behaviours upon energy systems, based upon ground truth data, through real operations or simulations of real-life scenarios.	Section 3.3 Section 4.3	A comprehensive assessment of carbon-footprint-related carbon footprint behaviours identified and investigated in academic literature over the last five years
	ST2.2.2 Operational best practice for Facilities & Asset Management Elicit best practice initiatives, in maximizing the reduction of energy usage behaviours within an organisation, linked to how a building runs its facilities and asset management. Behaviours identified (ST2.2.1) will be synthesized with known and emerging market trends to set clear guidelines for the long-term sustainability of privately run buildings.	Section 5	Carbon-footprint-related carbon footprint behaviours, as derived from academic literature, specific to the six Probono living labs, based on building type and location. Statistical analysis identifying the key behaviours specific to building type
	ST2.2.3 Mitigation measures and incentives for PROBONO stakeholders Apply quantitative and qualitative methods to identify mitigation measures and incentive models for stakeholders. Involve key stakeholders using ST1.4.1 findings, and provide input to relevant project activities (WP3, WP4 and WP9), including service and product design, and business modelling.	Section 3.3 Section 4.3 Section 6	Identification of relevant stakeholders, and an investigation of their carbon-footprint-related behaviours in specific building types at specific locations
DELIVERABLE			
<u>D2.2: Behavioural analysis and operational best practice</u> A classification of key behaviours as the basis for best practice guidelines to be incorporated in the design of operations. This report outlines a detailed analysis of energy-related behaviours identified and researched in recent academic literature (2018-2022), and identifies key overall carbon footprint behaviours (including 'good' and 'bad' behaviours) as well as those specific to living labs			

Table 1: Adherence to PROBONO's GA Deliverable & Tasks Descriptions

2 Approach to classifying key behaviours through a systematic review

2.1 Literature Search

With the aim of classifying carbon footprint behaviours most commonly under scrutiny in academic research, we conducted a literature search of all research articles published between 2018 and 2022 which mentioned the words ‘building’, ‘energy’ ‘occupant’ and ‘behaviour’/’behavior’ in their title, keywords or abstract. Two major bibliographic databases were screened, in order to ensure a representative assessment of recent academic research: 1) ScienceDirect (https://www.sciencedirect.com/), which hosts Elsevier academic journals and e-books, and 2) Web of Science (https://www.webofscience.com/, formerly known as Web of Knowledge), a publisher-independent multidisciplinary platform.

More than one thousand research articles matching the search criteria were exported as BibTex files and imported into bibliographic software (Zotero), where duplicates were excluded and the remaining 902 articles briefly assessed to ensure that they related to the behaviour of building occupants, rather than the behaviour of building materials or other physical properties. This left a final dataset of 609 research articles for systematic review. Table 2 outlines this selection process in greater detail.

Database	ScienceDirect	**Database**	Web of Science
Date of search	March 2022	**Date of search**	March 2022
Year published	2018-2022	**Year published**	2018-2022
Search inclusion criteria	Article title, keywords or abstract include the words ‘building’, ‘energy’, ‘occupant’ and ‘behaviour’/’behavior’	**Search inclusion criteria**	Article title, keywords or abstract include the words ‘building’, ‘energy’, ‘occupant’ and ‘behaviour’/’behavior’

Search syntax	N/A	**Search syntax**	AK=(building energy occupant behaviour behavior) OR AB=(building energy occupant behaviour behavior) OR TI=(building energy occupant behaviour behavior)
Excluding	• Review articles • Encyclopaedia • Book chapters • Data articles • Short communications	**Excluding**	• Review articles • Early Access • Proceeding papers
Number of articles returned by search results	469	**Number of articles returned by search results**	712
Number of articles in preliminary dataset	1181		
Inclusion criteria for final dataset	• Article relates to the behaviour of human occupants of buildings		
Exclusion criteria for final dataset	• Article relates to the behaviour of building materials or other non-human subjects (n = 293) • Duplicates (n = 279)		
Number of articles included in final dataset	609		

Table 2: The process for selecting academic literature for this systematic review

2.2 Data collection

These 609 articles were reviewed by three researchers, according to a predetermined set of criteria in line with other systematic reviews in this area (Alkhatib *et al.*, 2021; Amasyali and El-Gohary, 2021; Chen *et al.*, 2021; Dong *et al.*, 2021; Han *et al.*, 2021; Piselli *et al.*, 2021; Ramokone *et al.*, 2021; Zhu *et al.*, 2021; Fu *et al.*, 2022; Ji, Hong and Kim, 2022; Karyono *et al.*, 2022;

Krishnan, Kelly and Kim, 2022; Uddin *et al.*, 2022). Firstly, author information was recorded: the surname and academic discipline of the first author, as well as the country in which their affiliated university is located. This enables an assessment of the distribution and academic background of those conducting research into carbon footprint behaviours. Secondly, information about the city, country or region that is the focus of the research. Both categories are used in several existing systematic reviews (Heydarian *et al.*, 2020; Hu *et al.*, 2020). This provides an insight into the context of energy-related behaviours with regards typical temperature and weather conditions (for example, Norway vs Vietnam), as well as an impression of the overall geographical distribution of energy-related occupant behaviour research. Thirdly, the type of building being assessed, and the groups of occupants involved (e.g., residents, workers). Fourthly, and most central to our aim, is information about the carbon footprint behaviours under investigation, what behaviours were deemed by the researchers to be 'good' or 'bad' behaviours, and any factors that might influence these behaviours, both as relate to the occupants themselves (e.g., age, financial motivations) and external factors (e.g., weather conditions, air quality). Finally, we collected additional meta-data including the type of data collected, whether quantitative or qualitative research methods were used, and the journal in which the article was published. Methods used are considered to be of critical concern in systematic reviews (Negishi *et al.*, 2018; Zou *et al.*, 2018). Table 3 lists the data collected and reflects on the potential observations to be made. Data were entered into a shared Google Sheet, a screenshot of which is shown in Figure 1.

Data collected	**Potential observations**
Publication year	Is research into carbon footprint behaviours becoming more prolific?
Journal	Is carbon footprint behaviour research published by a narrow or broad range of journals?
First author discipline	What academic background do researchers have – social sciences, engineering, psychology?
First author region	What is the geographical distribution of researchers? Are they researching their own region or another?
Study location	Which country? Is it urban or rural? What is the climate like?

Research method	Is carbon footprint behaviour research more commonly conducted using quantitative data, or are interviews a more typical approach?
Good behaviours named	What types of behaviour do researchers associate with positive or negative energy uses or outcomes?
Bad behaviours named	
Groups discussed	What groups of people are of greatest interest to researchers and funding bodies? Whose behaviour is considered most important for academic study?
Groups discussed (further information)	
Building type discussed	What types of buildings are of greatest interest to researchers and funding bodies?
Building type discussed (further information)	
Carbon footprint behaviours discussed	Which carbon footprint behaviours attract the most attention from researchers and funding bodies?
Carbon footprint behaviours discussed (further information)	
External influences of carbon footprint behaviours discussed	What factors do researchers consider when investigating carbon footprint behaviours?
External influences of carbon footprint behaviours discussed (further information)	
Non-behavioural factors discussed	
Key focus of article	In what context is carbon footprint behaviour most often researched? Which areas attract the most attention from researchers and funding bodies?

Table 3: Data collected during the systematic review

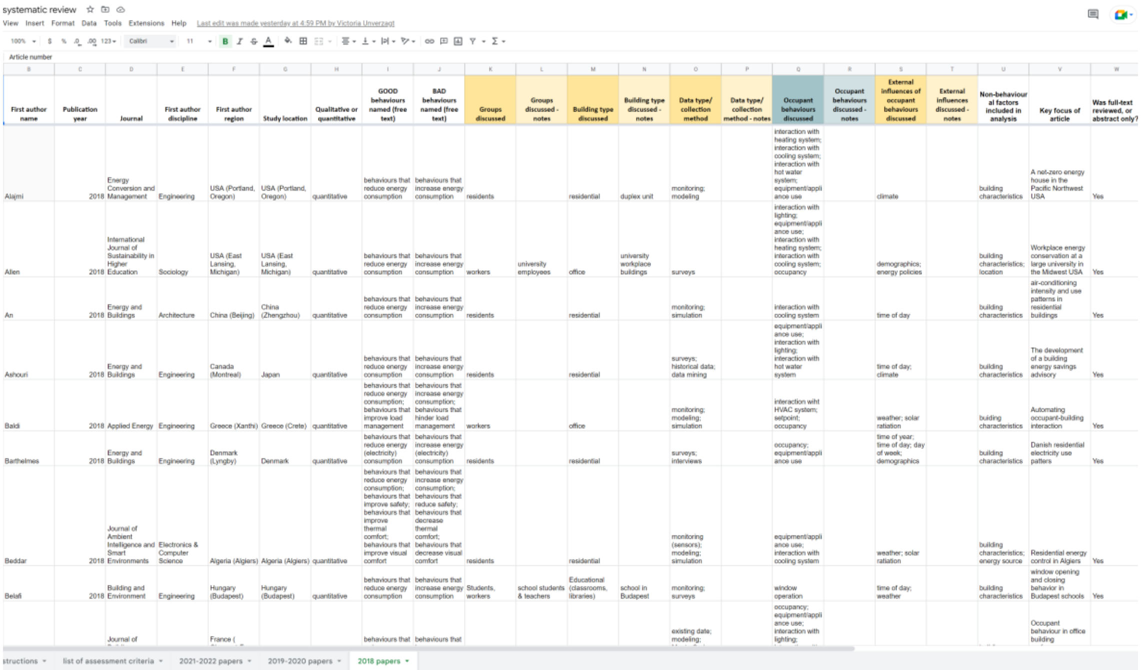


Figure 1: Screenshot showing an example of the data entry process

2.3 Data cleaning, categorisation, visualisation, and analysis

Once data is collected from all 609 articles, it must be cleaned before analysis. This process entails simplifying and categorising each data entry. Some examples of this process are shown in Table 4. Here we followed similar processes as set out in other systematic reviews (Burke, 2020; Jenkins *et al.*, 2021).

Article number	Carbon footprint behaviours discussed	Cleaned behaviours
1	opening/closing windows and doors	• window/door opening
2	Switching on fan as alternative to AC, opening windows for natural ventilation, switching off ACs when leaving the room, wearing light clothing	• window/door opening • A/C use • appropriate clothing

3	Heating and cooling setpoint	• thermostat setpoint
4	the use of smart technologies	• smart technologies use
7	interactions with heating, cooling, lighting, windows/doors opening, windows blinds and plug loads	• heating use • cooling use • lighting use • window/door opening • blind/shading use • plug loads
9	patterns of carbon footprint behaviour interactions with heating, cooling, lighting, equipment, windows, and shading collected	• heating use • cooling use • lighting use • window/door opening • blind/shading use • plug loads • equipment use
10	cooling setpoint; window operation	• window/door opening • A/C use
38	movement within building, time spent inside building, activities performed inside building	• movement within building • occupancy schedule • activities within building
90	interaction with the system, appliance operation, investing in energy saving home improvements	• interaction with system • plug use • energy saving investments
171	Generic - Thermal comfort Clothing adjustment (e.g., extra layer when cold) Window opening/ventilation (when present) Use of heating (when present)	• window/door opening • heating use • appropriate clothing

Table 4: Examples of data cleaning for carbon footprint behaviours

The processes of string searching, aggregation into groups, visualisation and analysis are conducted using Tableau (www.tableau.com), a business and analytics software platform. We follow the same approach to visualization as set out in McCauley et al (2022).

3 Preliminary analysis of the pilot dataset

3.1 Rationale for a pilot dataset

We initially performed a systematic review of a subset of our dataset, referred to in this report as the ‘pilot dataset’. This pilot dataset refers to articles published during 2021-2022 (n = 187), namely the most recent two years of the selected five-year period. This was a training process to approximate the range of behaviours, building types, occupant definitions likely to be described in the literature, as well as such metadata as their geographical context, the methodology used and the journals in which they were published. This pilot dataset was shared in its raw form with WP3 participants and was analysed to provide preliminary results to present to WP2 participants during the September 2022 monthly meeting. In this section we describe these 187 research articles.

3.2 Geographical locations, publishing journals, and data collection and analysis methods

3.2.1 Study locations

Of the 187 articles in the pilot dataset, 151 specified a single country as the focus of their research. Four articles named multiple countries as their study location, mainly European countries but also including some in the Middle East. Four articles dealt with one or more regions or continents (EU, USA/EU, East Asia/South America/Europe, the Middle East). The remaining 28 articles did not specify a geographical location. Of the 151 articles dealing with a single country, we find that the greatest proportion were studies of buildings in China (n = 30, or n = 4 if Hong Kong included, approximately 21%). The second most common country of interest was the USA (n = 19, 12.6%). Regionally, we find that studies focusing on Asian countries were the most common (n = 56, 37.1%), closely followed by those focusing on European countries (n = 54, 34.8%). While Asian studies predominantly focused on China as previously mentioned, European studies were dominated, albeit less starkly, by UK and Italy (11 articles each), followed by Spain and the Netherlands (5 articles each), and Germany and Switzerland (4 articles each). North, Central and South America comprised 19.9% of the 151 articles: the US (n = 19), Canada (n = 7), Brazil (n = 3) and Ecuador (n = 1) being the only countries represented. Oceania and

Africa made up the remaining 6.6% and 2.6% respectively: by far the greatest number of these were articles focusing on Australia (n = 9).

3.2.2 Publishing journals

We then analysed the frequency of journals in the pilot dataset. 'Energy and Buildings' was by far the most common journal to publish research on carbon footprint behaviours during 2021 and 2022 (n = 34), followed by 'Building and Environment' (n = 24). 'Applied Energy' and 'Journal of Building Engineering' shared third place with 12 articles, while 'Energies', 'Sustainability' and 'Journal of Cleaner Production' each published 8 articles each. In total, there were 56 journals represented among the 187 articles comprising the pilot dataset.

3.2.3 Data collection and analysis methods

Investigating the data collection methods used in the pilot dataset, we found that 183 of the 187 articles in the pilot dataset specified their research methods. Of these 183, the largest proportion used only data from sensors or other measuring devices (n = 40), and a further 49 used sensors in conjunction with other methods. Consequently, in the pilot dataset, sensors (and other measuring devices) were the most common source of data, both alone and in combination with other methods. The second most common research methodology referred to was modelling and simulation, where 35 articles mentioned this method in isolation and a further 50 mentioned it in combination with other methods. Surveys were the next most frequently cited research method; 19 articles mentioned surveys in isolation, and a further 39 combined them with other methods. Secondary data was relatively uncommon, with seven papers using pre-existing data alone, and a further 3 with other methods. Interviews were the sole source of data for only 3 articles and were complemented by other methods in a further 8 articles. Seven articles were literature reviews. Two articles named specific research methods: one used life cycle analysis, another choice experiments.

3.3 Buildings, occupants, and their behaviours

During the cleaning process of the pilot dataset, we observed 36 categories of carbon footprint behaviours, as shown in Figure 2. Further analysis of the complete dataset (articles published 2018-2022, n = 609) is likely to reveal further categories of behaviours which will be discussed in later sections. Figure 2 also shows the most common building types and occupant types investigated in the literature in 2021-2022.

3.3.1 Building types

Figure 2 shows that the most common type of building in the pilot dataset is *residential*, followed by *office* and then *educational* buildings. A small number of student residences and laboratories feature among the 187 articles, and several articles name specific buildings including greenhouses and industrial buildings.

3.3.2 Their occupants

As might be expected, given the distribution of building types in the pilot dataset, we find that most occupants are defined as ‘residents’, ‘workers’ and ‘students’. A small number of articles investigate the behaviours of professions and others specify the age range, income range or education level of the occupants (Figure 2).

3.3.3 Behaviours studied in the literature

In the pilot dataset, ‘interaction with system’ is the most commonly reported carbon footprint behaviour category. This a generic category referring to interaction with any building system. The next most common is ‘window/door opening (Figure 2). These behavioural categories will be assessed in relation to the main categories of building type and/or building occupant represented in the complete dataset.

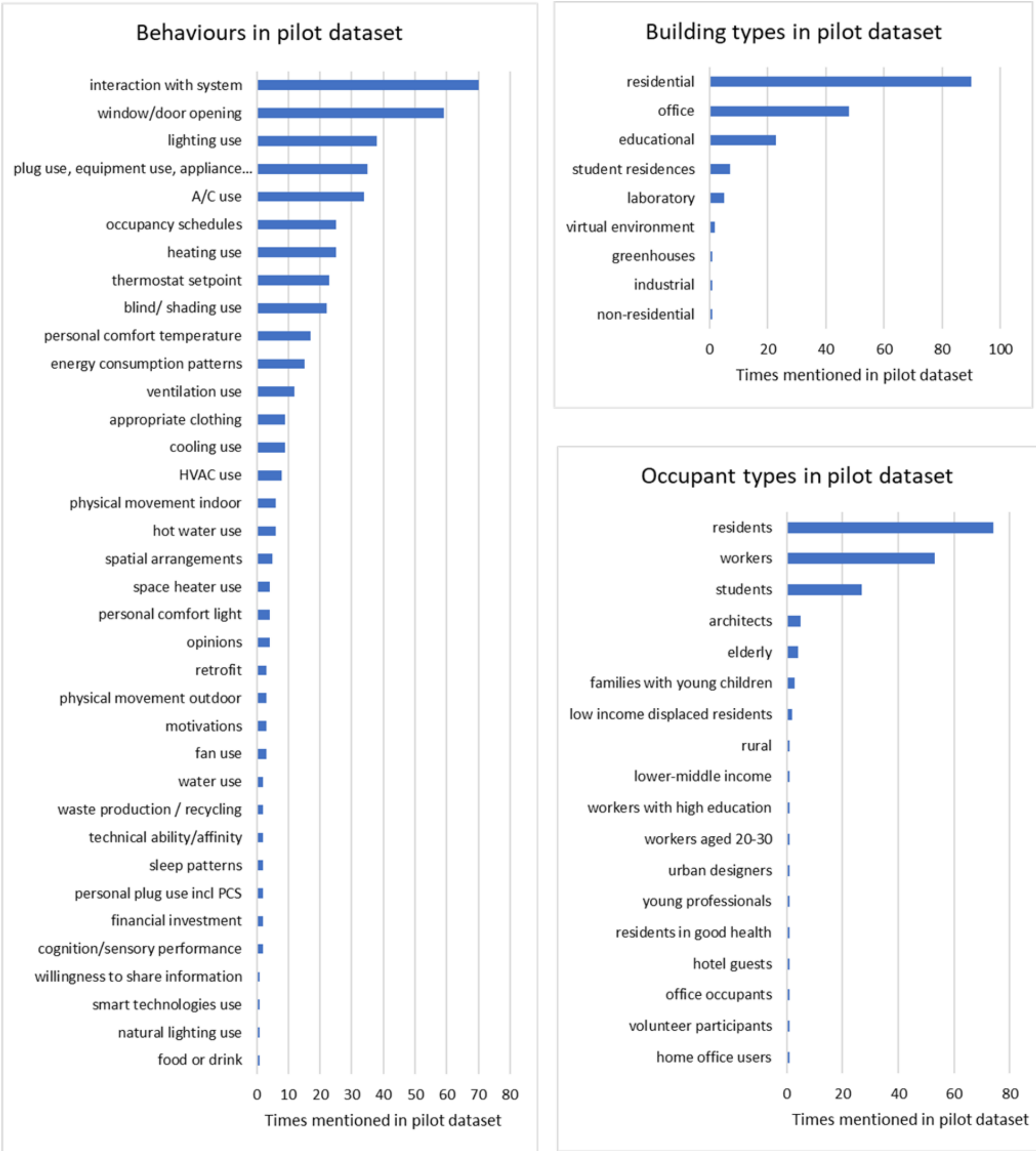


Figure 2: Behaviours, building types and occupant types identified in pilot dataset (literature published 2021-2022, n = 187)

4 Analysis of the complete dataset

4.1 Overview of the complete dataset

We go on to expand on these observations outlined in section 2, using the complete dataset, to provide a similar overview of all carbon footprint behaviour research published between 2018-2022.

4.2 Geographical locations, publishing journals, and data collection and analysis methods

4.2.1 Study locations

In the complete dataset, we find that, of the 609 articles, 498 specified a single country as the focus of their research. Fifteen articles named multiple countries as their study location, mainly within Europe (n = 9), as well as other international studies. Four articles dealt with one or more regions or continents (EU, USA/EU, East Asia/South America/Europe, the Middle East). The remaining 92 articles did not specify a geographical location. We find that the greatest proportion of articles were studies of buildings in China (n = 92, approximately 17%). The second most common country of interest was the USA (n = 83, 15%). Regionally, we find that studies focusing on European countries were the most common (n = 215, 40%) between 2018-2022, closely followed by those focusing on Asian countries (n = 167, 31%). This suggests that there has been a proportional increase in Asian carbon footprint behaviour studies in 2021-2022, compared with 2018-2022. While Asian studies predominantly focused on China as previously mentioned, European studies were dominated, albeit less starkly, by Italy and the UK (39 and 37 articles respectively), followed by Spain (n = 20), the Netherlands (n = 18) and France (n = 17), and Germany and Switzerland (14 and 10 articles respectively). North, Central and South America comprised 22% of articles: the US (n = 83), Canada (n = 23), Brazil (n = 5); Argentina, Chile, Colombia, Mexico and Ecuador making up the remaining 8 articles. Oceania and Africa made up the remaining 5% and 2% respectively, with 23 Australian studies and 2 in New Zealand, and more than half of the African studies focusing on Algeria and Egypt. Figure 3 shows these data from the complete dataset, as well as the location of the authors' affiliation in map form alongside a more detailed stacked bar chart.

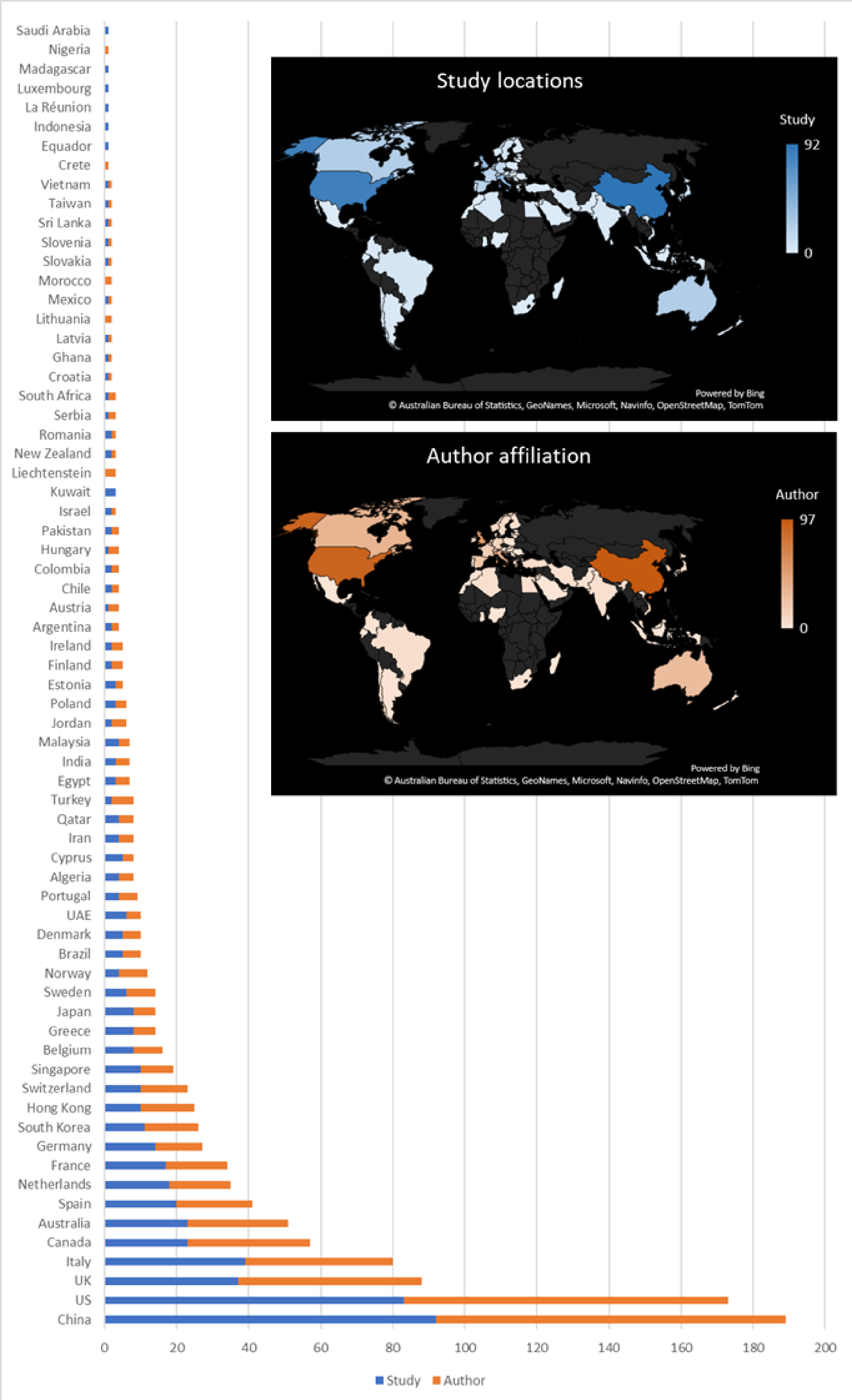


Figure 3: Maps and stacked bar chart showing the study locations and author locations of articles discussing carbon footprint behaviours during 2018-2022 (n = 609)

4.2.2 Publishing journals

In the complete dataset, which spanned 2018-2022, 'Energy and Buildings' continued to be by far the most common journal to publish research on carbon footprint behaviours (n = 138), again followed by 'Building and Environment' (n = 71). 'Applied Energy' was a clear third in the complete dataset with 41 articles, while 'Energies', 'Journal of Building Engineering' and 'Sustainability' had a similar number (n = 29, 27 and 26 respectively). 'Journal of Cleaner Production' did not feature as highly when articles from 2018-2020 were included, suggesting that its interest in carbon footprint behaviours is a comparatively recent phenomenon, in contrast to 'Applied Energy' who published proportionally more articles on carbon footprint behaviours in 2018-2020. In total, there were 113 journals represented among 605 articles. Table 5 shows the journals which were the most prolific publishers of carbon footprint behaviour research in the complete dataset, while Table 6 lists those which published only one such article during the five-year timeframe.

Journals with two or more articles	Number of articles
Energy & Buildings	138
Building & Environment	71
Applied Energy	41
Energies	29
Journal of Building Engineering	27
Sustainability	26
Energy	20
Sustainable Cities & Society	19
Journal of Cleaner Production	14
Energy Research & Social Science	10
Energy Efficiency	9
Journal of Building Performance Simulation	9
Building Simulation	8

Buildings	8
IEEE Access	8
Energy Procedia	7
Building Research & Information	6
Journal of Green Building	5
Renewable & Sustainable Energy Reviews	5
Science & Technology for the Built Environment	5
Advances in Building Energy Research	4
Atmosphere	4
Energy & Built Environment	4
Frontiers In Built Environment	4
Applied Thermal Engineering	3
Automation in Construction	3
Energy Conversion & Management	3
Energy for Sustainable Development	3
Facilities	3
Indoor & Built Environment	3
International Journal of Building Pathology & Adaptation	3
Journal of Housing & the Built Environment	3
Science of The Total Environment	3
Scientific Data	3
ACM Transactions on Design Automation of Electronic Systems	2
Building Services Engineering Research & Technology	2
Cognitive Systems Research	2
Frontiers in Energy Research	2
Frontiers In Sustainable Cities	2

Frontiers of Architectural Research	2
Journal of Architectural Engineering	2
Journal of Sensors	2
Light & Engineering	2
Procedia Computer Science	2
Renewable Energy	2
Resources, Conservation & Recycling	2
Smart & Sustainable Built Environment	2
Sustainable Energy Technologies & Assessments	2
Thermal Science	2

Table 5: Journals publishing two or more research articles on carbon footprint behaviours in 2018-2022

Journal	
Advanced Engineering Informatics	Information Sciences
Applied Sciences	Intelligent Buildings International
Architectural Science Review	International Journal of Built Environment & Sustainability
Building Engineering	International Journal of Environmental Research & Public Health
Building Performance Simulation	International Journal of Environmental Science & Technology
Built Environment Project & Asset Management	International Journal of GEOMATE
Bulding & Environment	International Journal of Integrated Engineering
Case Studies in Thermal Engineering	International Journal of Sustainability in Higher Education
Cities	Journal of Ambient Intelligence & Smart Environments

Cleaner & Responsible Consumption	Journal of Architectural Conservation
Cognitive Computation	Journal of Asian Architecture & Building Engineering
Computers in Industry	Journal of Energy Engineering
Concurrency & Computation Practice & Experience	Journal of Engineering, Design & Technology
Data in Brief	Journal of Heat Transfer
Energy & AI	Journal of Performance of Constructed Facilities
Energy & Buildings	Journal of Urban Planning & Development
Energy & Environment	Materials Today: Proceedings
Energy Economics	Mechanical Systems & Signal Processing
Energy Exploration & Exploitation	MethodsX
Energy Policy	Open House International
Energy Science & Engineering	PLOS ONE
Engineering Applications of Artificial Intelligence	Procedia Manufacturing
Engineering, Construction & Architectural Management	Proceedings of the Institution of Civil Engineers - Engineering Sustainability
Environment & Behavior	Public Health
Environment International	Quaestiones Geographicae
Environmental & Climate Technologies	Renewable & Sustainable Energy
Environmental & Resource Economics	Sensors (Basel)
Environmental Impact Assessment Review	Solar Energy
Habitat International	Sustainable Computing: Informatics & Systems
IEEE Embedded Systems Letters	Theoretical & Applied Climatology
IEEE Transactions on Consumer Electronics	Transactions On Emerging Telecommunications Technologies

IEEE Transactions on Control Systems Technology	Urban Science

Table 6: Journals publishing only one research article on carbon footprint behaviours in 2018-2022

4.2.3 Data collection and analysis methods

In the complete dataset (2018-2022), we found that 589 of the 609 articles specified their research methods. Of these 589, the largest proportion used data from sensors or other measuring devices (n = 320), over half of which used them in conjunction with other methods (e.g., modelling and simulation 31%, surveys 23%, interviews 5% and secondary data 3%). The second most common research methodology referred to was modelling and simulation, where 57 articles mentioned this method in isolation and a further 147 mentioned it in combination with other methods (sensors 49%, surveys 22%, secondary data 11% and interviews 3%). Surveys were the next most frequently cited research method; 69 articles mentioned surveys alone, and a further 121 combined them with other methods (sensors 38%, modelling and simulation 23%, interviews 10%, secondary data 6%, case studies 1%, and literature review, choice experiments and physical building audits each with 0.5%). Secondary data was relatively uncommon, with 41 papers using pre-existing data alone, and a further 43 alongside other methods (modelling and simulation 27%, surveys and sensors each 13%, interviews 1%). Interviews were the sole source of data for 9 articles and were complemented by other methods in a further 28 articles (surveys 51%, sensors 41%, modelling and simulation 19%, and secondary data, choice experiments and case studies 3% each). Eighteen articles were literature reviews solely, and a further three were literature reviews in combination with either theory, a case study, or a survey. Three articles named specific research methods: life cycle analysis, choice experiments and physical building audits.

It is noteworthy that the vast majority of research articles into carbon footprint behaviour published in 2018-2022 used sensors, modelling and simulation, surveys or secondary data – i.e., quantitative research methods, while only a small fraction used qualitative methods, i.e., interviews (Figure 4).

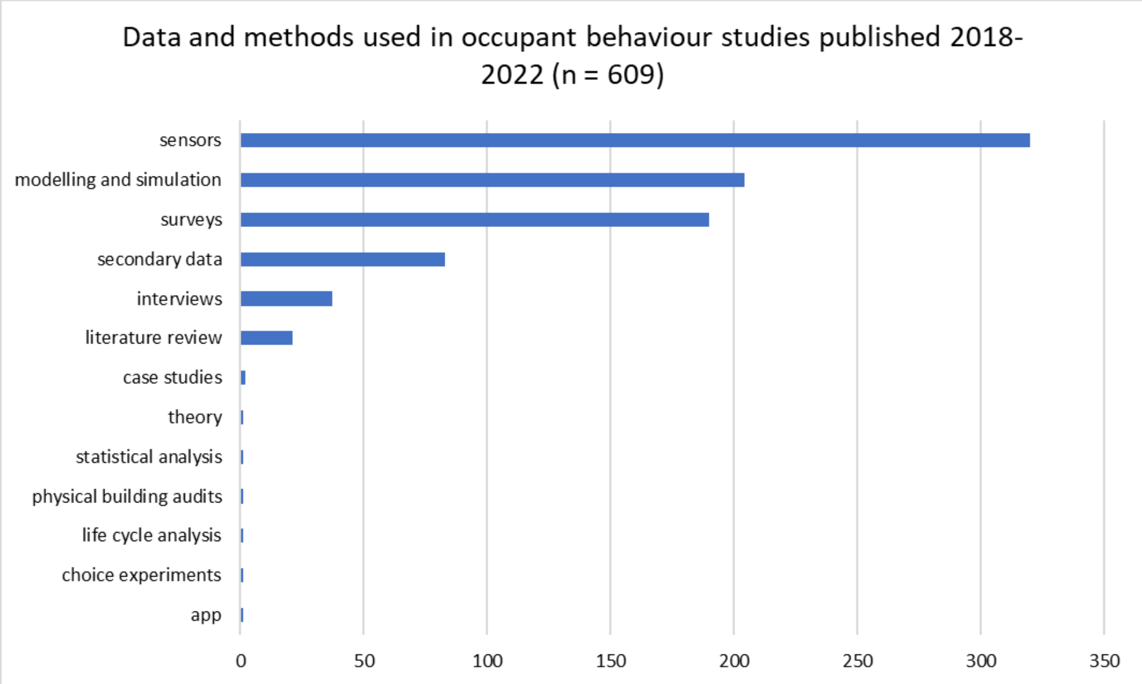


Figure 4: Data and methods used in carbon footprint behaviour studies published 2018-2022 (n = 609)

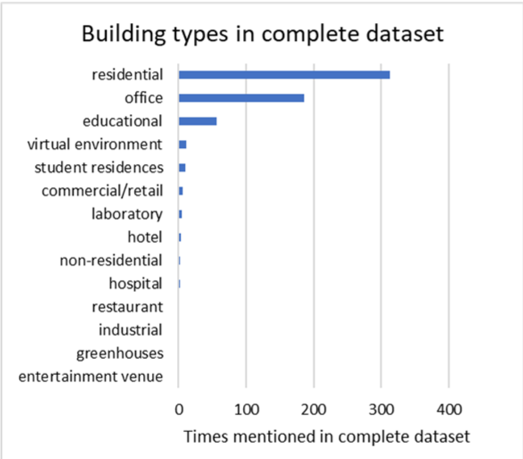
4.3 Buildings, occupants, and their behaviours

4.3.1 Building types

In this section, we expand on the observations from the pilot dataset made in section 2.3, by summarising the main types of behaviours, buildings and occupants discussed in literature published across the five-year period (2018-2022). The type of buildings researched in the literature has significance, as it is one of the key factors that we use to draw observations which are relevant to each living lab in section 4. As was seen in Figure 2, the predominant building type investigated in the pilot dataset was *residential*, followed by *office* buildings and *educational* establishments. Analysis of the complete dataset shows this trend to continue, with the addition of five further building types mentioned in small numbers of articles (Figure 5).

4.3.2 Their occupants

As in the pilot dataset, the three main classifications of occupants referred to in the complete dataset were *residents*, *workers,* and *students* (Figure 5), as might be expected from the predominance of residential, office and educational buildings in the literature. A small number of articles define residents or workers more minutely – for example, by age, educational level or income, or family status – or investigate other groups, such as building managers, architects, or hospital patients.



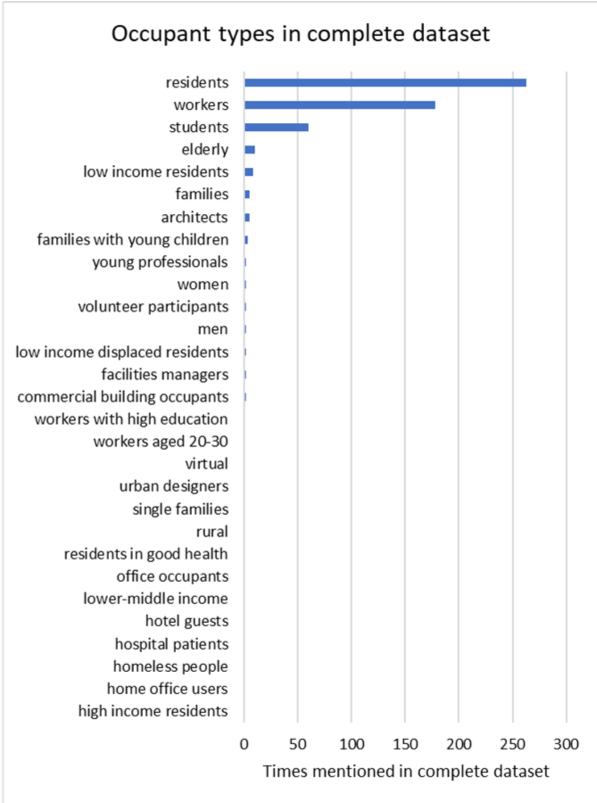


Figure 5: Building types and occupant types investigated in complete dataset (literature published 2018-2022, n = 609)

4.3.3 Behaviours studied in the literature

As can be seen in Figure 6, window or door opening behaviours were the most common carbon footprint behaviours researched in the last five years. 'Interaction with system' is a broad behavioural classification which covers occupant interactions with building systems in any type of building – so it is unsurprising that it is the second most common type of behaviour discussed in the literature. Lighting use is the third most common behaviour type in the reviewed articles. The use of equipment or appliances that require a power outlet (also be referred to as 'plug load'), closely followed by heating use, completes the top five behaviours researched in the literature.

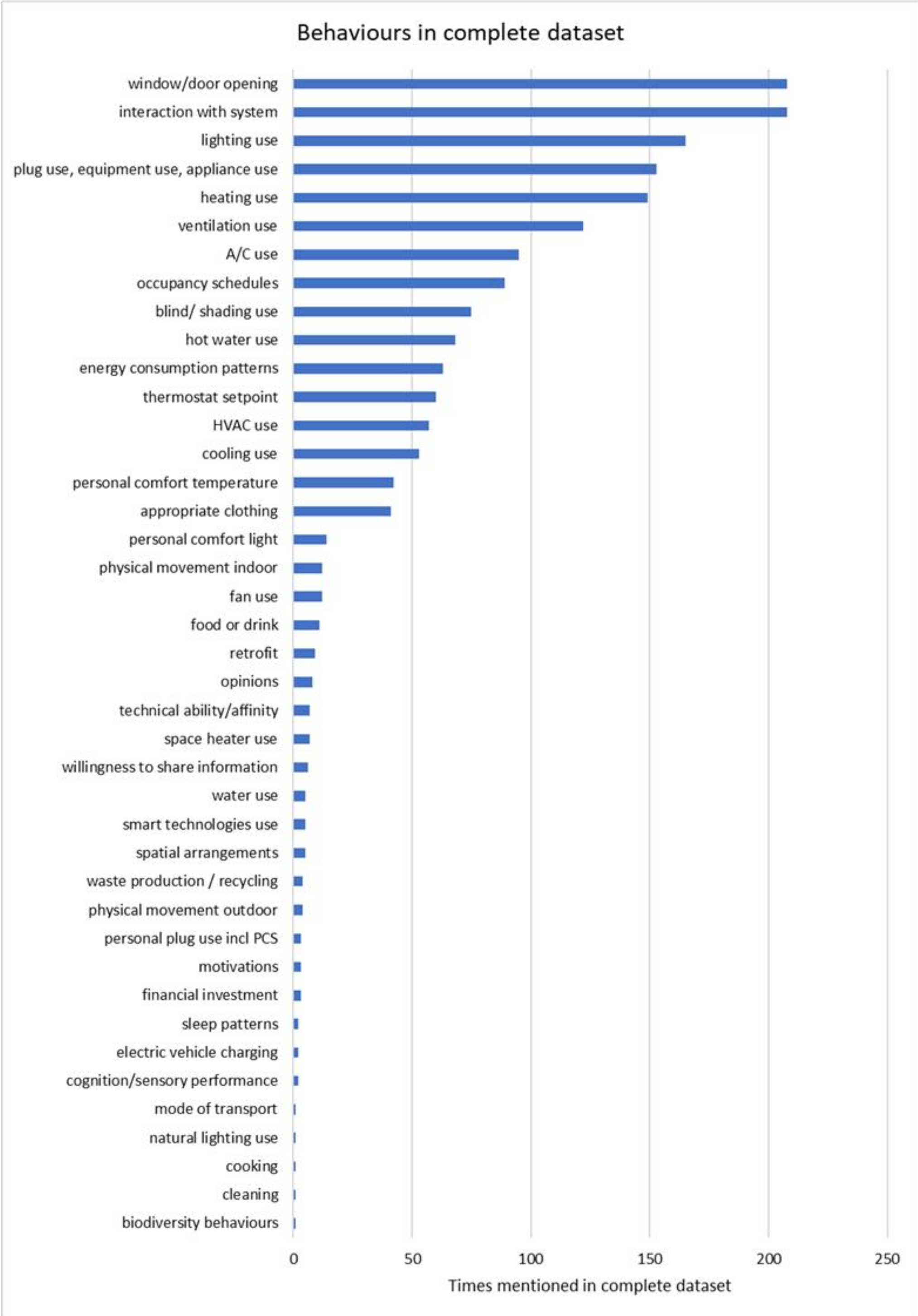


Figure 6: Behaviours identified in complete dataset (literature published 2018-2022, n = 609)

Arguably the behaviours that could be considered mid-ranking in importance were the use of ventilation, air conditioning/cooling systems, blinds or shading, and hot water. While our cleaning process endeavoured to exclude articles dealing solely with 'building occupancy' as opposed to 'occupant behaviours', occupancy schedules still featured as a common behaviour in the literature, as did energy consumption patterns. Thermostat setpoint and personal thermal comfort were among the mid-ranking behaviours, as was the use of appropriate clothing (e.g., putting on an extra layer when cold).

Less common behaviours could be grouped into further categories: with regards lighting, personal preferences about lighting, and the use of natural light are both mentioned infrequently. Physical activity both indoors and outdoors, spatial arrangements and the consumption of hot or cold food or drinks are researched in several articles. The use of small heating and cooling appliances (space heaters and fans), as well as personal comfort systems have been occasional topics of research. Retrofitting and its associated financial investment are mentioned in several articles, and occupants' affinity with and ability to use technology, in particular smart technologies, and their willingness to share information were behaviours occasionally touched on in the literature. In a similar vein, more qualitative matters such as occupants' opinions and motivations were investigated on only a small number of articles, reflecting the lack of qualitative research into carbon footprint behaviours. Other rarely featured behavioural categories included sleep patterns, transport-related behaviours (e.g., electric vehicle use/charging), biodiversity behaviours and waste generation and recycling.

4.3.4 'Good' and 'bad' behaviours

We also identified 'good' and 'bad' behaviours named in the research articles published during the five-year period (n = 609). Using Atlas.ti, we generated a word cloud for each, based on the frequency of the appearance of each adjective or verb in the list. Terms which appeared equally often in both word clouds were excluded, leaving only those terms which were unique to one word cloud (Figure 7). When visualised in this way, we see that 'good' and 'bad' behaviours are often described by antonyms, for example *efficient* vs *inefficient, regular* vs *irregular, predictable* vs *stochastic, conscious* vs *disengaged*. Emphasis appears to be on 'good' behaviours as restrained, appropriate, sustainable, responsible behaviours, as well as on awareness and education, and predictability.

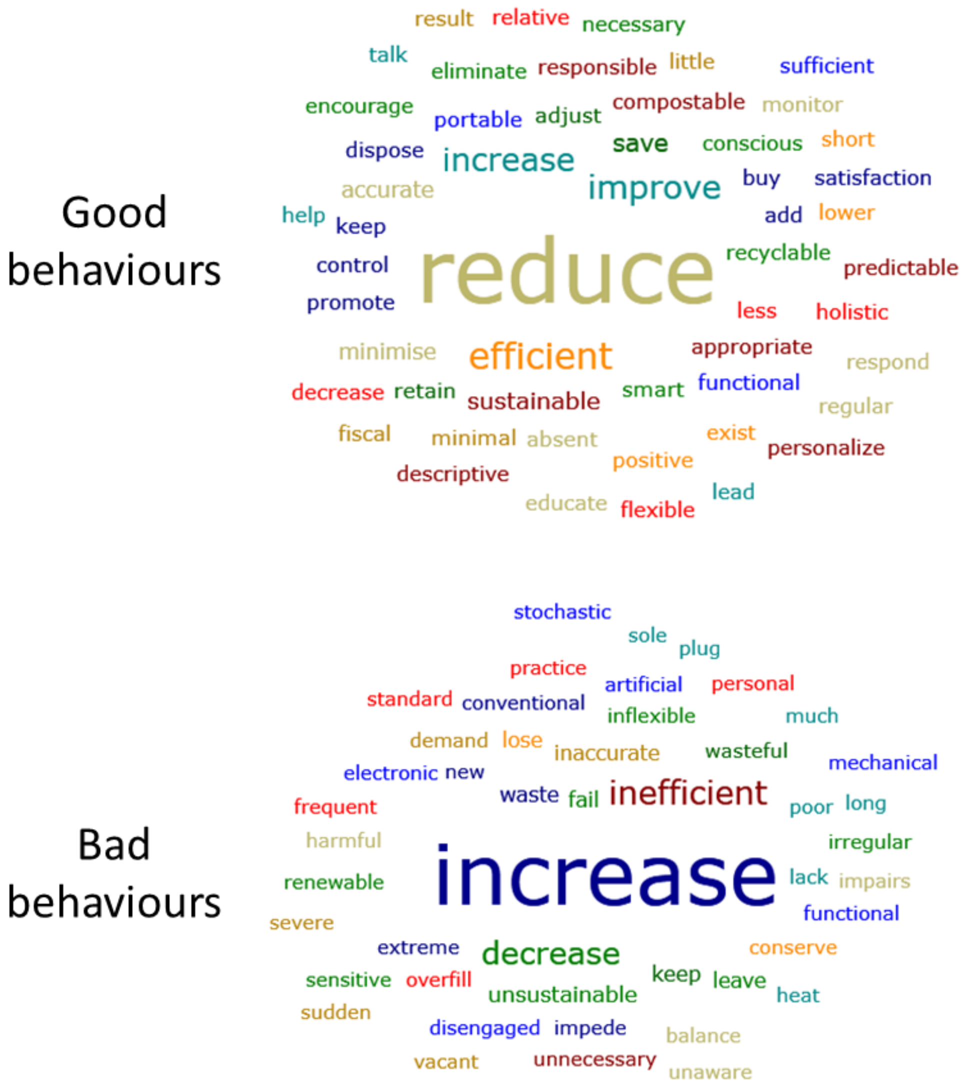


Figure 7: Word cloud of 'Good behaviours' and 'Bad behaviours' in occupant behaviour research articles published 2018-2022 (n = 609)

5 Living lab buildings, operational best practice, and carbon footprint behaviours

5.1 Overview of living labs and buildings

As a goal of this deliverable is to classify carbon footprint behaviours relevant to each of the six living labs, it is important to reflect on their characteristics. Living lab (LL) 1 is Dublin, where a County Hall and a range of other municipal buildings from social housing to a ferry terminal are being retrofitted. The Madrid living lab (LL2) encompasses retrofitting and new construction within a 300-hectare area, for the development of a neighbourhood containing residential and non-residential buildings. Porto's living lab (LL3) specifically deals with a business environment, the SONAE industrial campus. Brussels (LL4) focuses on the renovation of a private school and the improvement of transport and circular economy in the surrounding area. Aarhus (LL5) and Prague (LL6) living labs are engaged with the new construction and retrofitting of university campuses.

We find that the three most common building types examined in the academic literature of the last five years – residential, offices/workplaces and educational buildings – do indeed encompass the building types involved in each of the living labs, as shown in Table 7. Four of the six living labs (Dublin, Madrid, Aarhus and Prague) feature residential buildings, either for students or the general public. Five include office buildings or other workplaces (Dublin, Madrid, Porto, Aarhus and Prague), and three specifically focus on an educational environment (Brussels, Aarhus and Prague).

	Dublin	**Madrid**	**Porto**	**Brussels**	**Aarhus**	**Prague**
	LL1	**LL2**	**LL3**	**LL4**	**LL5**	**LL6**
Key Characteristics	Retrofitting, District, Residential and Non-residential buildings,	New construction, Retrofitting, District, Residential and non-residential	Retrofitting, Non-residential buildings, Private Funding	Retrofitting, Non-residential building, Public and Private Funding, Green Neighbourhood	New construction and retrofitting, public funding	Follower of Aarhus LL

	Public and Private Funding	buildings, Public and Private Funding		Clustering, User, Building Management and Operation, Citizen and Stakeholder Engagement and Behaviours		
Infrastructure / Urban facilities	Interconnected network of municipal buildings including a flagship public building (County Hall); 5 more GBN buildings including library, Ferry terminal, office spaces, 10 social housing units.	Geothermal District Heating and Cooling		De l'Autre Côté de l'Ecole (ACE)	University campus (lecture theatres, offices, study halls, libraries, cafes, shops, labs)	
Residential	✓	✓			✓	✓
Office/work	✓	✓	✓		✓	✓
Educational				✓	✓	✓
Energy focus		Geothermal	Solar		Solar	
Distinguishing features	Retrofitting diverse buildings	Resource infrastructure	Biodiversity	Transport, Buying locally		Passive cooling, Waste heat recovery

Table 7: Summary of Living Lab characteristics

All six living labs involve retrofitting, renovation, development of complex systems and an enhancement of green energy production and consumption, as well as a reduction of energy consumption overall. However, each living lab has its own distinct features and points of emphasis. Dublin LL's refitting of diverse municipal buildings, Madrid's use of geothermal energy for district heating and cooling and its emphasis on resource infrastructure, Brussels' focus on local transport and local purchasing, and Porto's use of large-scale solar energy generation are distinguishing features, as are Aarhus and Prague's focus on university campuses.

We aim to analyse the full dataset of 609 research articles in such a way as to isolate subsets of literature that best represent each of the living labs, according to building type (residential, workplace or educational). We will also identify research articles most relevant to each living lab, according to country and building type, and discuss in greater detail the attributes of the studies described, including the building types, occupant types, 'good behaviours', 'bad behaviours' and external factors influencing carbon footprint behaviours. The goal is to be able to characterise the main carbon footprint behaviours relevant to each living lab, using recent academic research as a guide.

5.2 Living lab buildings and behaviours – an overview of the dataset

Since the three main building types addressed in the literature are *residential*, *office* and *educational*, we sought to identify the predominant behaviours investigated in each of these building types separately. To identify a clear and representative view of each of the three building types, we selected only those research articles with dealt with only either residential, office or educational buildings, excluding those publications which dealt with more than one building type. This is to maximise any observable differences in the behaviour categories between the three main building types, and consequently to inform each living lab more robustly about the behaviours most likely to be of relevance in that particular environment, according to recent academic literature.

5.2.1 Residential buildings

For residential buildings, we identified 288 research articles of which 4 were virtual studies of residential buildings. The residential buildings studied included social housing, single-family houses, apartment buildings, high-rises, zero energy buildings, renovated and retrofitted buildings, Passivhaus-certified dwellings, retirement homes and historical buildings. Some articles specified the occupancy, the orientation (e.g., south-facing), and age of the building. These details can be found in the 'Building type discussed – notes' field of the bibliographic database. The occupant types in these purely residential-focused publications were, as might be expected, classified simply as 'residents' in the majority of cases, while a small number of articles further described the occupants on the basis of, for example, age, income, family or health status (Figure 8). These residential-only studies used the full range of methods described in section 3.3.3, in similar proportions as in the complete dataset (n = 609), as shown in Figure 9. The behaviours specified in these residential-only studies are outlined in Figure 10, with 'window/door opening' and generic 'interaction with system' as the joint most common named behaviours in residential buildings. Second was 'heating use', followed by the use of plug points/appliances, hot water, lighting and air conditioning.

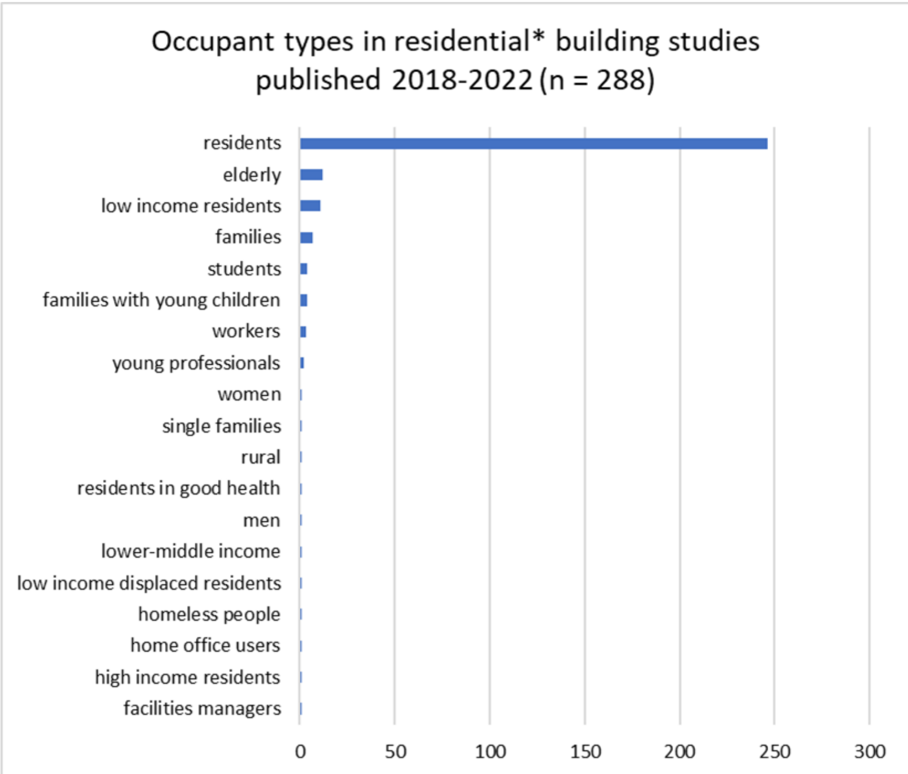


Figure 8: Occupant types in residential-only building studies published 2018-2022 (n = 288)

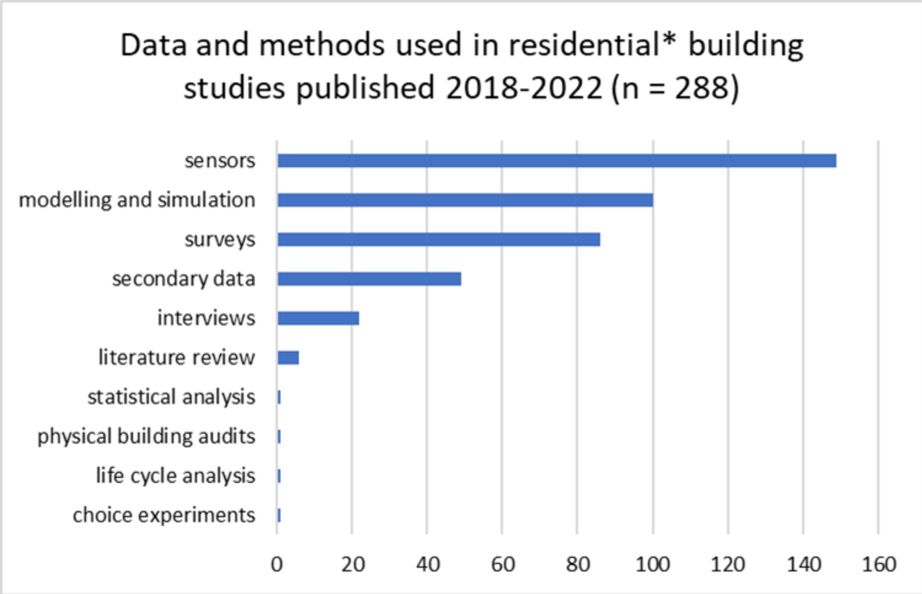


Figure 9: Data and methods used in residential-only building studies published 2018-2022 (n = 288)

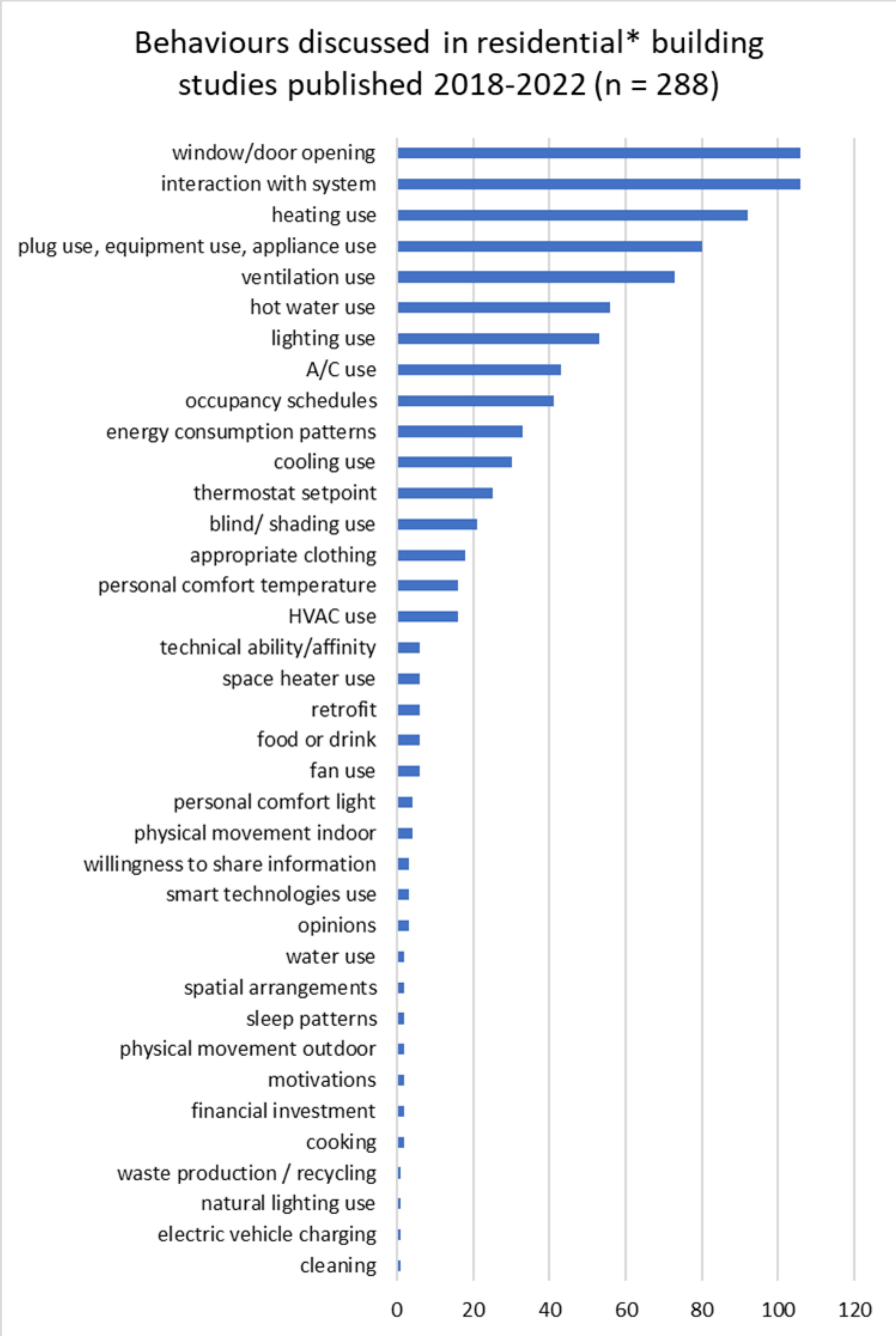


Figure 10: Behaviours discussed in residential-only building studies published 2018-2022 (n = 288)

5.2.2 Office buildings

For office buildings, we selected 161 research articles focusing on office buildings only (including 3 virtual studies). The office buildings studied included government buildings, private companies and university administration buildings and, in terms of layout, ranging from small single-occupant offices through meeting rooms to large open-plan offices. Some articles specified the floor space, the orientation (e.g., west-facing), and details such as whether they were naturally ventilated. These details can be found in the 'Building type discussed – notes' field of the bibliographic database. The occupant types in these purely office-focused publications were, as might be expected, classified simply as 'workers' in the majority of cases, while a very small number of articles specified the gender of the occupants, or were targeted towards the behaviours of facilities managers and architects/engineers (Figure 11).

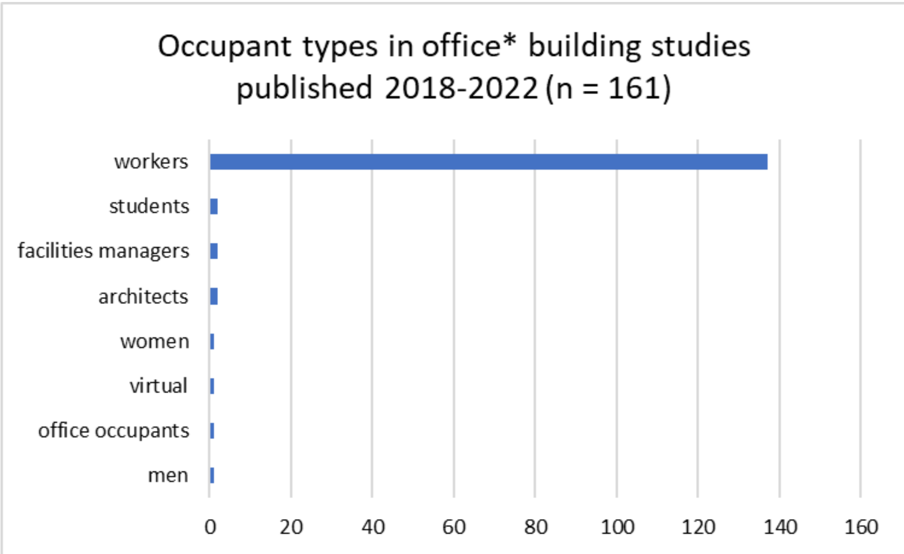


Figure 11: Occupant types in office-only building studies published 2018-2022 (n = 161)

These office-only studies used the full range of methods described in section 3.3.3, in similar proportions as in the complete dataset (n = 609), as shown in Figure 12. The behaviours specified in these office-only studies are outlined in Figure 13, with 'lighting use' as the most common named behaviour, followed by 'window/door opening' and generic 'interaction with system' as second and third most common. The use of plug points/appliances, blinds/shading and heating made up the fourth, fifth and sixth most common behaviour studied in office buildings.

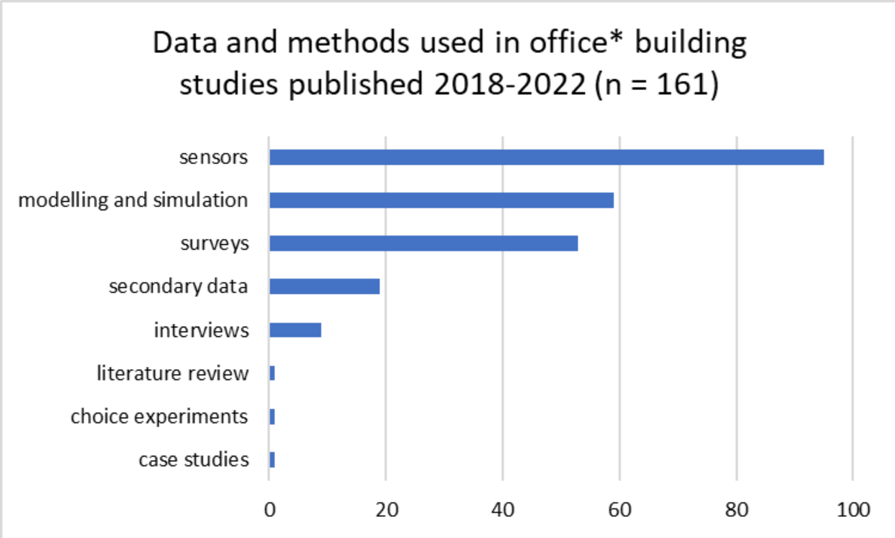


Figure 12: Data and methods used in office-only building studies published 2018-2022 (n = 161)

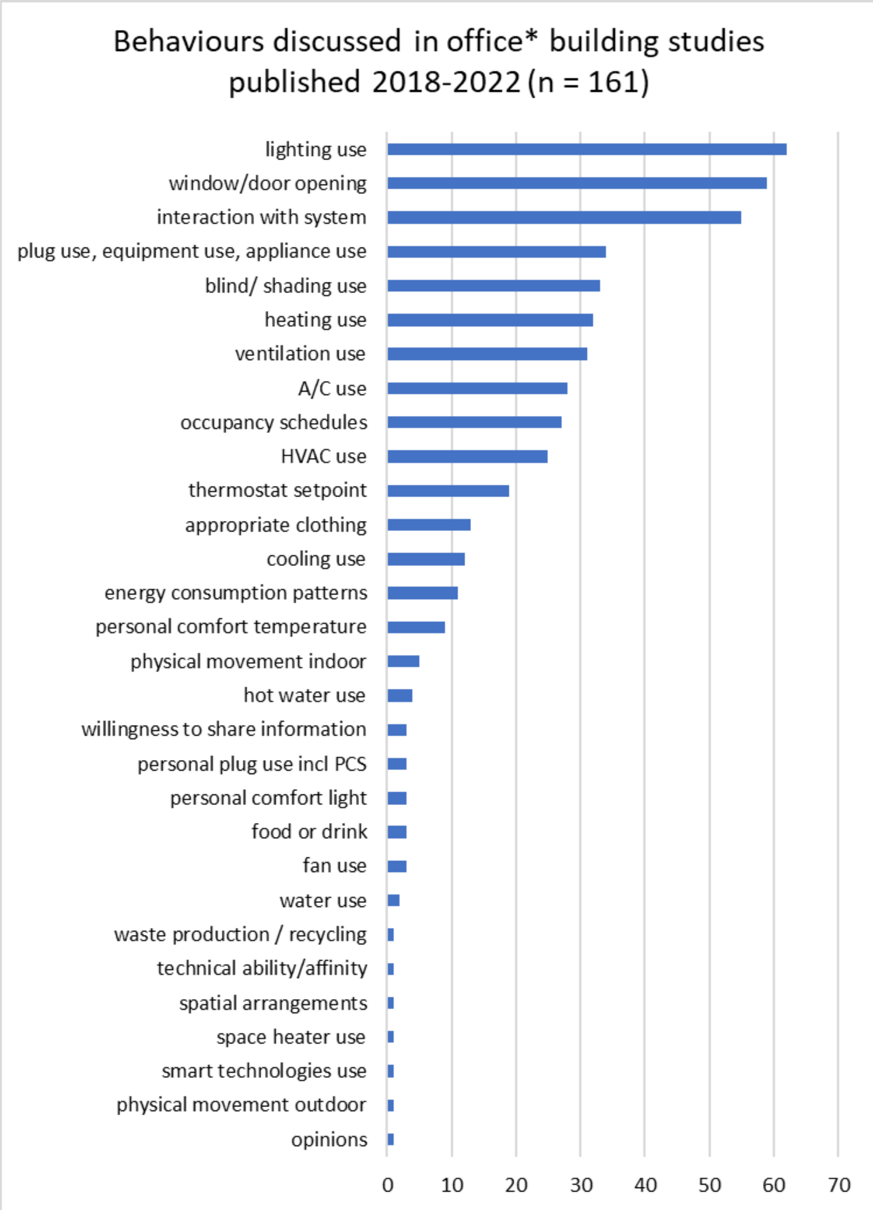


Figure 13: Behaviours discussed in office-only building studies published 2018-2022 (n = 161)

5.2.3 Educational buildings

For educational buildings, we identified 43 research articles of which one was a virtual study of educational buildings. One article included a student residence, two included university laboratories and one a student health centre alongside teaching rooms, computer rooms and libraries. The educational buildings studied ranged from kindergartens, secondary schools and university buildings, including research buildings. These details can be found in the 'Building type discussed – notes' field of the bibliographic database. The occupant types in these purely educational-focused publications were students and university employees, with a small number of studies specifying volunteer participants (Figure 14, left). These educational-only studies used a narrower range of methods compared to those of residential and office building studies, probably due to the smaller number of purely educational research articles. They were in similar proportions as in the complete dataset (n = 609), however, as shown in Figure 14 (right). The behaviours specified in these educational-only studies are outlined in Figure 15, with 'lighting use' as the most common named behaviour, followed by plug points/appliances/equipment use, generic 'interaction with system' and 'window/door opening'. The use of heating, air conditioning, ventilation and shading systems were of mid-range focus in the literature alongside occupancy schedules.

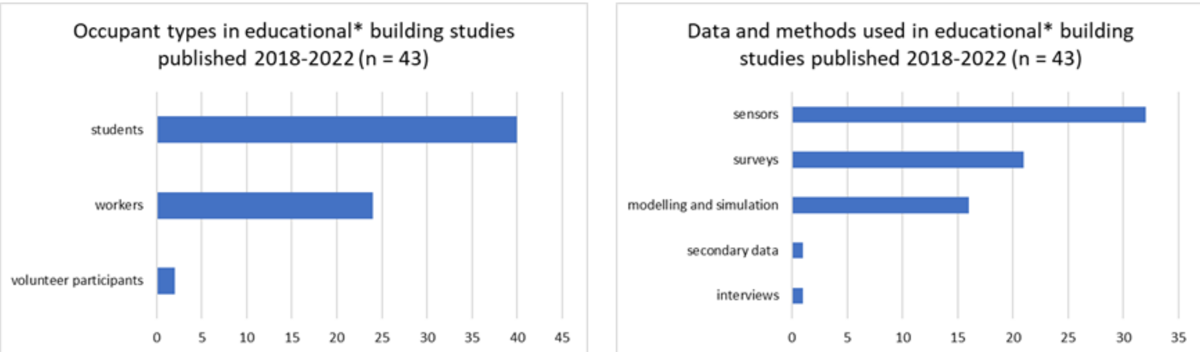


Figure 14: Occupant types, and data and methods used in educational-only building studies published 2018-2022 (n = 43)

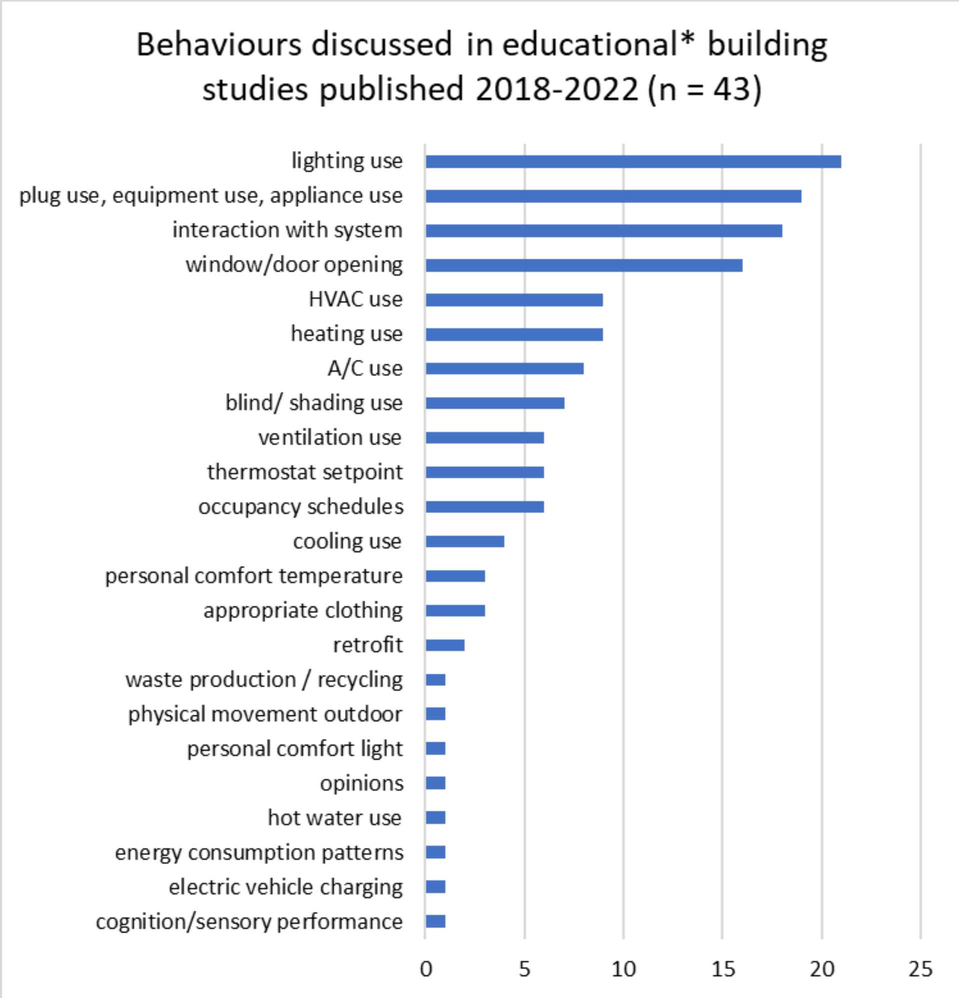


Figure 15: Behaviours discussed in educational-only building studies published 2018-2022 (n = 43)

5.3 Living lab buildings and behaviours – a statistical analysis of the dataset

We can see that there are some visible differences in the main behavioural categories between residential, office and educational buildings. For example, it could be inferred that window/door opening behaviour is viewed as a more important occupant behaviour trait in residential buildings than behaviours relating to lighting use (Figure 10), at least in terms of the amount of attention received in research publications. In contrast, we can see from Figures 13 and 15 that this is not the case in office or educational buildings, where occupants' lighting use behaviours are the most frequently mentioned in the literature.

However, to determine if these observations are statistically significant, we conduct a chi-squared test to assess whether the actual number of times each behaviour is mentioned in the literature differs from what would be expected if all behaviour categories were mentioned equally often in residential-building articles, office-building articles, and educational-building articles. The results of this chi-square test are shown in Table 8. The p value reflects the probability that these observations are due to random chance, rather than genuine differences between the building types. For example, a p value of 0.05 indicates that there is a less than 5% probability that the observations are random, while a p value of 0.001 denotes a 1% probability. Therefore, a lower p value indicates greater statistical significance.

	Residential		Office		Educational		p
Behaviour category	N (obs)	N (exp)	N (obs)	N (exp)	N (obs)	N (exp)	
A/C use	43	46.1	28	25.4	8	7.5	0.77
appropriate clothing	19	19.9	13	10.9	2	3.2	0.64
blind/ shading use**	**21**	**35.6**	**33**	**19.6**	**7**	**5.8**	**0.00045**
cleaning	1	0.58	0	0.32	0	0.09	0.70
cognition/sensory performance	**0**	**0.58**	**0**	**0.32**	**1**	**0.09**	**0.0082**
cooking	2	1.2	0	0.64	0	0.19	0.49
cooling use	30	26.9	12	14.8	4	4.3	0.63
electric vehicle charging	1	1.2	0	0.64	1	0.19	0.13
energy consumption patterns	*33*	*26.3*	*11*	*14.5*	*1*	*4.2*	*0.081*
fan use	6	5.3	3	2.9	0	0.85	0.62
financial investment	2	1.2	0	0.64	0	0.19	0.49
food or drink	6	5.3	3	2.9	0	0.85	0.62
heating use*	**92**	**77.7**	**32**	**42.8**	**9**	**12.5**	**0.042**
hot water use**	**56**	**35.6**	**4**	**19.6**	**1**	**5.8**	**8.3E-07**
HVAC use**	**16**	**29.2**	**25**	**16.1**	**9**	**4.7**	**0.00061**
interaction with system	106	104.5	55	57.6	18	16.9	0.90
lighting use**	**53**	**79.4**	**62**	**43.7**	**21**	**12.8**	**2.0E-05**
motivations	2	1.2	0	0.64	0	0.19	0.49

natural lighting use	1	0.58	0	0.32	0	0.09	0.70
occupancy schedules	41	43.2	27	23.8	6	7.0	0.71
opinions	3	2.9	1	1.6	1	0.47	0.66
personal comfort light	5	4.7	3	2.6	0	0.75	0.65
personal comfort temperature	17	16.4	9	9.0	2	2.6	0.91
personal plug use incl PCS*	**0**	**1.8**	**3**	**0.96**	**0**	**0.28**	**0.042**
physical movement indoor	4	5.8	6	3.2	0	0.94	0.14
physical movement outdoor	2	2.3	1	1.3	1	0.38	0.57
plug use, equipment use, appliance use	*80*	*77.7*	*34*	*42.8*	*19*	*12.5*	*0.074*
retrofit	*6*	*4.7*	*0*	*2.6*	*2*	*0.75*	*0.082*
sleep patterns	2	1.2	0	0.64	0	0.19	0.49
smart technologies use	3	2.3	1	1.3	0	0.38	0.73
space heater use	6	4.1	1	2.3	0	0.66	0.32
spatial arrangements	2	1.8	1	0.96	0	0.28	0.85
technical ability/affinity	6	4.1	1	2.3	0	0.66	0.32
thermostat setpoint	25	29.2	19	16.1	6	4.7	0.48
ventilation use	74	64.8	31	35.8	6	10.5	0.15
waste production / recycling	1	1.8	1	0.96	1	0.28	0.34
water use	2	2.3	2	1.3	0	0.38	0.66
willingness to share information	3	3.5	3	1.9	0	0.57	0.54
window/door opening	107	106.3	59	58.5	16	17.2	0.96

*Table 8: Chi-square test to determine if observed counts (Nobs) differ significantly from expected counts (Nexp) (** p<0.001, *p<0.05)*

We see in Table 8 that several behavioural categories are mentioned in the literature more frequently in certain building types, even if the threshold for statistical significance is corrected for multiple testing (i.e., 0.05/41 behavioural categories = 0.001). Blind/shading use, hot water use, HVAC use, and lighting use appear to fit this criterion (**), while heating use and personal plug use are statistically significant without correcting for multiple comparisons (*). For example, if all the mentions of blind/shading use were distributed proportionally across studies of residential buildings, office buildings and educational buildings, we would expect approximately 36 mentions in residential-building articles, 20 in office-building articles and 6 in educational-building articles. While in practice we find proportionally fewer in residential building articles (21) and proportionally more in office building articles (33) and educational building articles (7), giving a p value of 0.00045. In contrast, and even more starkly, hot water use is mentioned proportionally more often in residential building articles (56 times vs an expected 36) and proportionally less often in office (4 times vs an expected 20) and educational (1 time vs an expected 6 times) building articles, giving a highly significant p value of 8.3E-07. A summary and interpretation of these statistically significant findings can be found in Table 9. In brief, we could infer that the use of hot water and heating are deemed to be behaviours of most importance to residential buildings than office or educational buildings, while the use of lighting, blinds/shading and HVAC are considered of greater importance in office and educational buildings than in residential. Personal plug use has received proportionally more attention in studies of office buildings, suggesting that this behaviour may be considered most relevant and specific to that building type. Cognition/sensory performance, while proportionally more common in educational building studies, was mentioned only once across the three building types and therefore the sample size is too small to draw meaningful conclusions.

Behaviour category	p	Residential	Office	Educational
hot water use	8.3E-07	More common	Less common	Less common
lighting use	2.0E-05	Less common	More common	More common
blind/ shading use	0.00045	Less common	More common	More common
HVAC use	0.00061	Less common	More common	More common
cognition/sensory performance	0.0082	Less common	Less common	More common
heating use	0.042	More common	Less common	Less common
personal plug use incl PCS	0.042	Less common	More common	Less common

Table 9: Summary of behaviour categories that show evidence of being important in particular building types

All other behavioural categories were investigated in equal measure across all three building types, statistically speaking, suggesting that they are broadly relevant to buildings in general. It could be argued that those behavioural categories achieving p values between 0.05 and 1.0 might be considered potentially more relevant in one building type over another – these include plug/appliance/equipment use ('less common' in office, $p = 0.07$), and energy consumption patterns and retrofitting ('more common' in residential, $p = 0.08$).

5.4 Living lab buildings and behaviours – identifying mitigation measures and incentives

Having identified behaviour categories that show statistical evidence of being more relevant in certain building types, we can shift focus from building type to geographical region. The six living labs are situated in Dublin, Madrid, Porto, Brussels, Aarhus, and Prague. The complete dataset contains information on the study location of each article, to the city level. However, the relative proportion of studies from those six countries are comparatively low in the dataset, As can be seen in Figure 3, Spain is ranked 7th, Belgium 15th, Denmark 21st, Portugal 23rd and Ireland 36th among the 68 countries represented in the literature, in terms of number of studies, while there are no occupant behaviour publications at all for the Czech Republic. These comparatively low numbers preclude any quantitative analysis of the data on a national level for the six living lab countries. Instead, we will describe the details of studies performed on buildings in Ireland, Spain, Portugal, Belgium, and Denmark, with a view to providing behavioural information tailored to each living lab where possible, thereby offering some early indications on potential mitigation measures and incentives.

5.4.1 Carbon footprint behaviour studies in Ireland: LL1 Dublin

Beginning with LL1 (Dublin), we have only two carbon footprint behaviour articles to discuss. A quantitative study was conducted in 2018 focusing on predicting air temperatures in a naturally ventilated nearly zero energy building (Cork Institute of Technology), using monitoring and modelling, investigating the behaviours of students and staff. There was a focus on reducing energy consumption and increasing visual comfort, and the specific behaviours investigated were interactions with ventilation system, and with shading/blinds, as well as occupancy.

Mitigation measures identified included non-behavioural factors that were taken into consideration, such as building characteristics, ventilation system characteristics and temporal factors (Donovan, Sullivan and Murphy, 2019). The second Irish article was a 2022 qualitative study looking at Netherlands, Belgium, Ireland, conducting semi-structured interviews of residents of small zero energy homes, aiming to evaluate the existing market to establish a business model of affordable zero energy houses (Ebrahimigharehbaghi, Heijden and Elsinga, 2022).

5.4.2 Carbon footprint behaviour studies in Spain: LL2 Madrid

LL2 (Madrid) should benefit from Spain being among the most researched European countries for carbon footprint behaviours. There were 12 articles focusing solely on residential buildings in Spain, two of which specifically mentioned Madrid. A 2019 study used sensors to monitor thermal comfort and indoor air quality in low-income housing in Madrid and Sevilla, considering occupants' window operation as well as interaction with heating and cooling systems (Fernández-Agüera *et al.*, 2019). In a second article, the climatic conditions of Stuttgart, Madrid, Stockholm, and Melbourne were used to create a cognitive model of energy-relevant human building interaction. Using a TRNSYS room model, virtual carbon footprint behaviour included window opening, use of appropriate clothing and use of heating, alongside external factors of lighting and noise conditions, privacy and security (von Grabe, 2020).

However, most carbon footprint behaviour studies into residential buildings in Spain focused on Sevilla. A study investigated the performance of phase change materials-based solutions towards passive and low-energy cooling through a parametric study carried out in TRNSYS, to identify main design criteria for their optimal implementation. In this instance, the window-opening behaviour of residents of a multi-family building in Sevilla were the main focus (Lizana *et al.*, 2019). An article investigating real energy and economic savings of retrofitting actions, depending on different energy-related occupant scenarios, was conducted using secondary data and surveys into the energy (particularly heating) consumption of families in an apartment building from 1942 (Serrano-Jiménez *et al.*, 2019). Another looked at indoor environment and energy performance in historic residential buildings, using monitoring and modelling and investigating residents' interactions with cooling and ventilation systems, as well as occupancy (Caro and Jose Sendra, 2020). An article investigated the influence of ventilation patterns and long periods of occupation on indoor environmental quality, focusing on ventilation habits among elderly residents of apartments, particularly night-time ventilation (Serrano-Jiménez *et al.*, 2020). Another focused on the energy performance and indoor environmental quality of dwellings within listed buildings in Sevilla, looking into residents' window operation, electric radiator use, and heat set-point, generating energy models and measuring rates of indoor air temperature (Caro and Jose Sendra, 2021).

After Sevilla, the next most researched city was Bilbao, with three articles into residential carbon footprint behaviours. A 2018 study investigated individual metering and charging of heat and domestic hot water using smart meters. Behaviours centred around the efficiency of heating and hot water usage (Terés-Zubiaga *et al.*, 2018). A later study conducted modelling and simulation using secondary data (Population and Housing Census from the National Statistics Institute) to investigate residential heating consumption - their carbon footprint behaviour focus was exclusively on heating use (Fernandez, Portillo and Flores, 2020). The third evaluated multi-zone heating systems, including space heating use by families and the elderly, using Design Builder software but also financial analysis (Rodríguez-Pertuz *et al.*, 2020).

Other cities studies were Barcelona, San Sebastian and Castelló de la Plana, A 2019 study investigated energy refitting in apartments in Barcelona, using sensors. Behaviours discussed included the use of appliances and ventilation, particularly window operation (Casquero-Modrego and Goñi-Modrego, 2019). Another investigated overheating in Spanish Passivhaus buildings due to new NZEB requirements. This paper focused on thermal comfort of residents of six Passivhaus-certified dwellings in San Sebastian, using sensor and survey data. As well as considerations of weather and age/condition of the building, this study also took urban heat island effect into account (Rodriguez Vidal, Otaegi and Oregi, 2020). A 2021 article reported findings of statistical analysis of real energy consumption data, with the aim of determining the influence of occupant demographics in real building energy consumption in households in Castelló de la Plana (Braulio-Gonzalo *et al.*, 2021).

Two other articles investigated Spanish residential buildings alongside those in other European countries, but neither focused on Madrid (Escandón, Silvester and Konstantinou, 2018; Castano-Rosa *et al.*, 2021).

In contrast to the comparative plethora of articles investigating residential buildings, there were only two which studied carbon footprint behaviour in solely *office* buildings in Spain. One was an article researching energy optimization in smart buildings, considering both the planning and operational aspects and to propose an optimal deployment of the WSN inside a building in Barcelona. The article focused on thermal comfort and movement within the building, alongside window opening behaviours and use of lights, and emphasised the preference for predictable rather than stochastic behaviours (Sembroiz *et al.*, 2019). The second was a study in Bilbao seeking to "propose a method for the decoupling of the HLC of in-use buildings into its transmission (UA) and infiltration (Cv) heat loss coefficients". Carbon footprint behaviour discussions focused on general thermal comfort and heat loss behaviour, alongside external factors of weather, air quality, and space design features (Uriarte *et al.*, 2021).

5.4.3 Carbon footprint behaviour studies in Portugal: LL3 Porto

There are four articles in total which investigate carbon footprint behaviours in Portugal. However, as all four of these deal with residential buildings, rather than non-residential buildings (Table 7), direct comparisons with the studies described may be limited. But, as can be seen from Table 8, most of the carbon footprint behaviour categories identified in the literature are equally relevant to residential and non-residential buildings, some relevant information for LL3 may be gleaned from the following four research articles, especially as two of them focused on Porto.

One of these reported a sensor-based study of a multi-family building in Porto aiming to establish the seasonality of specific actions and the parameters that define them. Residents' window-opening and blind/shading use were investigated, alongside non-behavioural factors of weather, seasonality and wall/floor/window specifications (Pereira and Ramos, 2020). A second sought to evaluate renovation strategies for social housing, with a focus on energy poverty. The authors used sensors, surveys, and Design Builder simulation to investigate the ventilation behaviours of low-income residents, alongside considerations of weather (temperature), financial motivations, energy poverty concerns, and perceptions of comfort and satisfaction with the building in terms of its age and condition (Seabra *et al.*, 2021).

Beyond Porto, a third study used surveys and sensors to investigate thermal performance and comfort in residential buildings with glazed balconies in Braga, taking into account residents' occupancy and interactions with cooling and heating systems (Fernandes *et al.*, 2020). The fourth article to mention Portugal was a study looking at the effects of change in temperatures in the residential sector cooling demand, using Eurostat data from multiple countries (Cyprus, Finland, Greece, Israel, Portugal, Slovakia, Spain) (Castano-Rosa *et al.*, 2021).

5.4.4 Carbon footprint behaviour studies in Belgium: LL4 Brussels

Our search criteria found six publications investigating carbon footprint behaviours in buildings in Belgium, and a further one which also looked at the Netherlands and Ireland (previously described in relation to LL1). Five of the six Belgium-only studies investigated residential buildings while one looked at office buildings. There were no carbon footprint behaviour studies investigating Belgian educational buildings but as previously stated in relation to Porto, most carbon footprint behaviours are equally relevant to residential, office and educational buildings, in terms of research attention.

The single article looking at office buildings was an investigation of sensor unreliability in a lighting company in Turnhout, focusing on occupancy and occupant movement around the building (Papatsimpa and Linnartz, 2018).

Regarding residential building publications, the most relevant location-wise may be a study in Brussels investigating ventilation strategies in single-family houses with an emphasis on indoor air quality (Belmans *et al.*, 2019).

The rest of the articles were located in other cities around Belgium. One investigated thermal adaptation in net zero energy buildings in Liège, using sensors and interviewing residents. The main points of interest in this study were interaction with heating, ventilation and lighting, appliance use and window operation (Attia, 2020). An article seeking to establish representative carbon footprint behaviour for the archetype building in Genk used modelling and simulation of survey data on residents' interaction with heating systems and thermal setpoint (De Jaeger *et al.*, 2020). An article aiming to make design phase energy predictions used modelling and simulation using data on Leuven residents' appliance usage, and interactions with heating, lighting and ventilation systems, as well as data on weather, temporal information and building characteristics (Miyamoto, Allacker and De Troyer, 2020). Finally, a study investigating window use in Ghent apartment and single-family dwellings during different seasons. The authors installed window sensors on every window, which provided direct measurements on window use behaviours (Verbruggen *et al.*, 2021).

5.4.5 Carbon footprint behaviour studies in Denmark: LL5 Aarhus

Publications specifically relevant to LL5 (i.e., behaviours in buildings in Denmark) consist of five articles focusing on residential buildings. Our search criteria did not find any articles about Danish office or educational buildings.

Two of these five articles were studies of residential buildings in Aarhus. One article presents a "clustering-based knowledge discovery in databases method", investigating heating use behaviours in Aarhus residents using data from smart meters. Weather conditions, family size, occupancy patterns, age and condition of building and age of occupant were also taken into account (Gianniou *et al.*, 2018). The second Aarhus-focused publication, investigating how building design and technologies influence heat-related habits, looked at the efficiency of heating behaviours of residents using survey and secondary data. Behavioural factors considered include window use, the use of temperature-appropriate clothing, the consumption of temperature-appropriate food and drink, heating, and hot water use. Non-behavioural factors included the age/condition of the building, socioeconomic factors, age, gender, immigration status and family status of the occupant, as well as floor area and number of rooms (Hansen, Gram-Hanssen and Knudsen, 2018).

Outside Aarhus, one study performed qualitative and quantitative analyses of the effectiveness of in-home displays in reducing electricity, heat and water use in Copenhagen apartments (Canale *et al.*, 2021). The remaining two publications were Denmark-wide carbon footprint behaviour articles, both published using Danish Time Use Survey (TUS) data, a diary-based resource of 9640 individuals from 4679 households during 2008/09. These studies aimed to “profile energy-related daily activities” and occupancy patterns, and to create a “generic building cluster that could resemble any mix of building archetypes and occupancy” respectively (Barthelmes *et al.*, 2018; Wang, Li and You, 2018).

5.4.6 Carbon footprint behaviour studies in the Czech Republic: LL6 Prague

There were no studies in our complete dataset (n = 609) which focused on the Czech Republic, and thus resulting indications towards possible mitigation measure or incentives were impossible to derive.

6 Conclusion

6.1 Findings

In this report, we have systematically reviewed and summarised the academic literature investigating energy-related carbon footprint behaviours in buildings over the last five years. We have listed the carbon footprint behaviours researched in academic studies, ranking them by their frequency of appearance in the literature. This analysis assumes that the more frequently a carbon footprint behaviour features in academic studies, the more important it is deemed to be by researchers, funders and journal editors and peer-reviewers. Following that assumption, the most widely studied carbon footprint behaviours are accordingly the most important. We went on to both statistically and descriptively tailor these observations to each living lab, first on the basis of building type and secondly on geographic location. The overarching observations gleaned from this analysis are summarised in the next section.

6.2 Lessons learned

Several conclusions can be learned from this analysis of the academic literature into carbon footprint behaviours. Firstly, research in this social and behavioural area is overly reliant on quantitative methods, and that there is a dearth of qualitative research. Secondly, that there are some carbon footprint behaviours which are deemed more relevant to certain building types, if the assumption outlined in section 5.1 is adhered to: specifically, heating and hot water use in residential buildings, lighting, blind/shading and HVAC use in office and educational buildings, and personal plug use in office buildings. Thirdly, that many of the most common carbon footprint behaviours in the literature are equally relevant to all three building types: for example, window opening behaviour, the use of appliances/equipment and air conditioning, and the wearing of appropriate clothing for the temperature. Fourthly, from a living lab perspective, that there is a lack of published carbon footprint behaviour studies in Ireland and particularly the Czech Republic.

6.3 Next steps

This dataset, representing all recent research into building occupants' behaviours with regards to carbon footprint, will be made available as an open-access database of research articles indexed for their most relevant content. A link to the read-only repository can be found in the Appendix. It should be emphasised that the database as it currently stands is at an early stage: we plan to expand this database over the next four years by continuing this systematic review process both retrospectively (pre-2018) and in real time (newly published literature from 2022 onwards). In the long-term, we intend to supplement it with other types of social data, including polling data, for example from Eurobarometer (https://europa.eu/eurobarometer/).

As indicated in our recent report part of McCauley and Pettigrew (2022) into the justice aspects of the European Green Deal, there is a lack of social and behavioural data on a non-project-specific basis. Our work seeks to expand the breadth and depth of usable data for understanding the behavioural implications of constructing buildings throughout Europe. This is an important goal for work package 2. The urgency of building social data for the project means that starting with existing research is logical. To this end, we also propose conducting a similarly designed systematic review on interview transcripts collected by PROBONO participants, for the purpose of identifying the types of carbon footprint behaviours that are of greatest interest and relevance to stakeholders.

References

Alkhatib, H. *et al.* (2021) 'Deployment and control of adaptive building facades for energy generation, thermal insulation, ventilation and daylighting: A review', *Applied Thermal Engineering*, 185, p. 116331. Available at: https://doi.org/10.1016/j.applthermaleng.2020.116331.

Amasyali, K. and El-Gohary, N. (2021) 'Machine learning for occupant-behavior-sensitive cooling energy consumption prediction in office buildings', *Renewable and Sustainable Energy Reviews*, 142, p. 110714. Available at: https://doi.org/10.1016/j.rser.2021.110714.

Attia, S. (2020) 'Spatial and Behavioral Thermal Adaptation in Net Zero Energy Buildings: An Exploratory Investigation', *SUSTAINABILITY*, 12(19). Available at: https://doi.org/10.3390/su12197961.

Barthelmes, V.M. *et al.* (2018) 'Profiling occupant behaviour in Danish dwellings using time use survey data', *Energy and Buildings*, 177, pp. 329–340. Available at: https://doi.org/10.1016/j.enbuild.2018.07.044.

Belmans, B. *et al.* (2019) 'Set-up and evaluation of a virtual test bed for simulating and comparing single- and mixed-mode ventilation strategies', *Building and Environment*, 151, pp. 97–111. Available at: https://doi.org/10.1016/j.buildenv.2019.01.027.

Braulio-Gonzalo, M. *et al.* (2021) 'Contribution of households' occupant profile in predictions of energy consumption in residential buildings: A statistical approach from Mediterranean survey data', *Energy and Buildings*, 241, p. 110939. Available at: https://doi.org/10.1016/j.enbuild.2021.110939.

Burke, M.J. (2020) 'Energy-Sufficiency for a Just Transition: A Systematic Review', *Energies*, 13(10), p. 2444.

Canale, L. *et al.* (2021) 'Do in-home displays affect end-user consumptions? A mixed method analysis of electricity, heating and water use in Danish apartments', *Energy and Buildings*, 246, p. 111094. Available at: https://doi.org/10.1016/j.enbuild.2021.111094.

Caro, R. and Jose Sendra, J. (2020) 'Evaluation of indoor environment and energy performance of dwellings in heritage buildings. The case of hot summers in historic cities in Mediterranean Europe', *SUSTAINABLE CITIES AND SOCIETY*, 52. Available at: https://doi.org/10.1016/j.scs.2019.101798.

Caro, R. and Jose Sendra, J. (2021) 'Are the dwellings of historic Mediterranean cities cold in winter? A field assessment on their indoor environment and energy performance', *ENERGY AND BUILDINGS*, 230. Available at: https://doi.org/10.1016/j.enbuild.2020.110567.

Casquero-Modrego, N. and Goñi-Modrego, M. (2019) 'Energy retrofit of an existing affordable building envelope in Spain, case study', *Sustainable Cities and Society*, 44, pp. 395–405. Available at: https://doi.org/10.1016/j.scs.2018.09.034.

Castano-Rosa, R. *et al.* (2021) 'Cooling Degree Models and Future Energy Demand in the Residential Sector. A Seven-Country Case Study', *SUSTAINABILITY*, 13(5). Available at: https://doi.org/10.3390/su13052987.

Chen, S. *et al.* (2021) 'The impacts of occupant behavior on building energy consumption: A review', *Sustainable Energy Technologies and Assessments*, 45, p. 101212. Available at: https://doi.org/10.1016/j.seta.2021.101212.

De Jaeger, I. *et al.* (2020) 'Aggregating set-point temperature profiles for archetype-based: simulations of the space heat demand within residential districts', *JOURNAL OF BUILDING*

PERFORMANCE SIMULATION, 13(3), pp. 285–300. Available at: https://doi.org/10.1080/19401493.2020.1727567.

Dong, B. *et al.* (2021) 'Occupant behavior modeling methods for resilient building design, operation and policy at urban scale: A review', *Applied Energy*, 293, p. 116856. Available at: https://doi.org/10.1016/j.apenergy.2021.116856.

Donovan, A.O., Sullivan, P.D.O. and Murphy, M.D. (2019) 'Predicting air temperatures in a naturally ventilated nearly zero energy building: Calibration, validation, analysis and approaches', *Applied Energy*, 250, pp. 991–1010. Available at: https://doi.org/10.1016/j.apenergy.2019.04.082.

Ebrahimigharehbaghi, S., Heijden, H. van der and Elsinga, M. (2022) 'Sustainable business model of affordable zero energy houses: Upscaling potentials', *Journal of Cleaner Production*, 344, p. 130956. Available at: https://doi.org/10.1016/j.jclepro.2022.130956.

Escandón, R., Silvester, S. and Konstantinou, T. (2018) 'Evaluating the environmental adaptability of a nearly zero energy retrofitting strategy designed for Dutch housing stock to a Mediterranean climate', *Energy and Buildings*, 169, pp. 366–378. Available at: https://doi.org/10.1016/j.enbuild.2018.03.079.

Fernandes, J. *et al.* (2020) 'Thermal Performance and Comfort Condition Analysis in a Vernacular Building with a Glazed Balcony', *ENERGIES*, 13(3). Available at: https://doi.org/10.3390/en13030624.

Fernandez, J., Portillo, L. del and Flores, I. (2020) 'A novel residential heating consumption characterisation approach at city level from available public data: Description and case study', *Energy and Buildings*, 221, p. 110082. Available at: https://doi.org/10.1016/j.enbuild.2020.110082.

Fernández-Agüera, J. *et al.* (2019) 'Thermal comfort and indoor air quality in low-income housing in Spain: The influence of airtightness and occupant behaviour', *Energy and Buildings*, 199, pp. 102–114. Available at: https://doi.org/10.1016/j.enbuild.2019.06.052.

Fu, Y. *et al.* (2022) 'Utilizing commercial heating, ventilating, and air conditioning systems to provide grid services: A review', *Applied Energy*, 307, p. 118133. Available at: https://doi.org/10.1016/j.apenergy.2021.118133.

Gianniou, P. *et al.* (2018) 'Clustering-based analysis for residential district heating data', *Energy Conversion and Management*, 165, pp. 840–850. Available at: https://doi.org/10.1016/j.enconman.2018.03.015.

von Grabe, J. (2020) 'Using the Instance-Based Learning Paradigm to Model Energy-Relevant Occupant Behaviors in Buildings', *COGNITIVE COMPUTATION*, 12(1), pp. 71–99. Available at: https://doi.org/10.1007/s12559-019-09672-w.

Han, M. *et al.* (2021) 'The reinforcement learning method for occupant behavior in building control: A review', *Energy and Built Environment*, 2(2), pp. 137–148. Available at: https://doi.org/10.1016/j.enbenv.2020.08.005.

Hansen, A.R., Gram-Hanssen, K. and Knudsen, H.N. (2018) 'How building design and technologies influence heat-related habits', *BUILDING RESEARCH AND INFORMATION*, 46(1, SI), pp. 83–98. Available at: https://doi.org/10.1080/09613218.2017.1335477.

Heydarian, A. *et al.* (2020) 'What drives our behaviors in buildings? A review on occupant interactions with building systems from the lens of behavioral theories', *Building and Environment*, 179, p. 106928. Available at: https://doi.org/10.1016/j.buildenv.2020.106928.

Hu, S. *et al.* (2020) 'A systematic review of occupant behavior in building energy policy', *Building and Environment*, 175, p. 106807. Available at: https://doi.org/10.1016/j.buildenv.2020.106807.

Jenkins, R.H. *et al.* (2021) 'The relationship between austerity and food insecurity in the UK: A systematic review', *EClinicalMedicine*, 33, p. 100781. Available at: https://doi.org/10.1016/j.eclinm.2021.100781.

Ji, C., Hong, T. and Kim, H. (2022) 'Statistical analysis of greenhouse gas emissions of South Korean residential buildings', *Renewable and Sustainable Energy Reviews*, 156, p. 111981. Available at: https://doi.org/10.1016/j.rser.2021.111981.

Karyono, K. *et al.* (2022) 'The role of hygrothermal modelling for different housing typologies by estimating indoor relative humidity, energy usage and anticipation of fuel poverty', *Building and Environment*, 207, p. 108468. Available at: https://doi.org/10.1016/j.buildenv.2021.108468.

Krishnan, D., Kelly, S. and Kim, Y. (2022) 'A Meta-Analysis Review of Occupant Behaviour Models for Assessing Demand-Side Energy Consumption', *ENERGIES*, 15(3). Available at: https://doi.org/10.3390/en15031219.

Lizana, J. *et al.* (2019) 'Passive cooling through phase change materials in buildings. A critical study of implementation alternatives', *Applied Energy*, 254, p. 113658. Available at: https://doi.org/10.1016/j.apenergy.2019.113658.

McCauley, D. *et al.* (2022) 'Which states will lead a just transition for the Arctic? A DeePeR analysis of global data on Arctic states and formal observer states', *Global Environmental Change*, 73, p. 102480.

Miyamoto, A., Allacker, K. and De Troyer, F. (2020) 'Considering Occupant Behaviour in Building Energy Simulations along the Design Process: From a Semi-dynamic to a Dynamic Model', in V. Corrado et al. (eds) *PROCEEDINGS OF BUILDING SIMULATION 2019: 16TH CONFERENCE OF IBPSA*. Int Bldg Performance Simulat Assoc (Building Simulation Conference Proceedings), pp. 2205–2212. Available at: https://doi.org/10.26868/25222708.2019.210540.

Negishi, K. *et al.* (2018) 'An operational methodology for applying dynamic Life Cycle Assessment to buildings', *Building and Environment*, 144, pp. 611–621. Available at: https://doi.org/10.1016/j.buildenv.2018.09.005.

Papatsimpa, C. and Linnartz, J.P.M.G. (2018) 'Propagating sensor uncertainty to better infer office occupancy in smart building control', *Energy and Buildings*, 179, pp. 73–82. Available at: https://doi.org/10.1016/j.enbuild.2018.08.039.

Pereira, P.F. and Ramos, N.M.M. (2020) 'Influence of Occupant Behaviour on the State of Charge of a Storage Battery in a nearly-Zero Energy Building', in J. Kurnitski and T. Kalamees (eds) *12TH NORDIC SYMPOSIUM ON BUILDING PHYSICS (NSB 2020)*. (E3S Web of Conferences). Available at: https://doi.org/10.1051/e3sconf/202017216010.

Piselli, C. *et al.* (2021) 'Assessing users' willingness-to-engagement towards Net Zero Energy communities in Italy', *Renewable and Sustainable Energy Reviews*, 152, p. 111627. Available at: https://doi.org/10.1016/j.rser.2021.111627.

Ramokone, A. *et al.* (2021) 'A review on behavioural propensity for building load and energy profile development – Model inadequacy and improved approach', *Sustainable Energy Technologies and Assessments*, 45, p. 101235. Available at: https://doi.org/10.1016/j.seta.2021.101235.

Rodriguez Vidal, I., Otaegi, J. and Oregi, X. (2020) 'Thermal Comfort in NZEB Collective Housing in Northern Spain', *SUSTAINABILITY*, 12(22). Available at: https://doi.org/10.3390/su12229630.

Rodríguez-Pertuz, M.L. *et al.* (2020) 'Feasibility of zonal space heating controls in residential buildings in temperate climates: Energy and economic potentials in Spain', *Energy and Buildings*, 218, p. 110006. Available at: https://doi.org/10.1016/j.enbuild.2020.110006.

Seabra, B. *et al.* (2021) 'Low Energy Renovation of Social Housing: Recommendations on Monitoring and Renewable Energies Use', *SUSTAINABILITY*, 13(5). Available at: https://doi.org/10.3390/su13052718.

Sembroiz, D. *et al.* (2019) 'Planning and operational energy optimization solutions for smart buildings', *Information Sciences*, 476, pp. 439–452. Available at: https://doi.org/10.1016/j.ins.2018.06.003.

Serrano-Jiménez, A. *et al.* (2019) 'Decision-support method for profitable residential energy retrofitting based on energy-related occupant behaviour', *Journal of Cleaner Production*, 222, pp. 622–632. Available at: https://doi.org/10.1016/j.jclepro.2019.03.089.

Serrano-Jiménez, A. *et al.* (2020) 'Indoor environmental quality in social housing with elderly occupants in Spain: Measurement results and retrofit opportunities', *Journal of Building Engineering*, 30, p. 101264. Available at: https://doi.org/10.1016/j.jobe.2020.101264.

Terés-Zubiaga, J. *et al.* (2018) 'Effects of individual metering and charging of heating and domestic hot water on energy consumption of buildings in temperate climates', *Energy Conversion and Management*, 171, pp. 491–506. Available at: https://doi.org/10.1016/j.enconman.2018.06.013.

Uddin, M.N. *et al.* (2022) 'Influence of interior layouts on occupant energy-saving behaviour in buildings: An integrated approach using Agent-Based Modelling, System Dynamics and Building Information Modelling', *Renewable and Sustainable Energy Reviews*, 161, p. 112382. Available at: https://doi.org/10.1016/j.rser.2022.112382.

Uriarte, I. *et al.* (2021) 'Decoupling the heat loss coefficient of an in-use office building into its transmission and infiltration heat loss coefficients', *Journal of Building Engineering*, 43, p. 102591. Available at: https://doi.org/10.1016/j.jobe.2021.102591.

Verbruggen, S. *et al.* (2021) 'Evaluation of the relationship between window use and physical environmental variables: consistency, seasonality and diversity', *JOURNAL OF BUILDING PERFORMANCE SIMULATION*, 14(4), pp. 366–382. Available at: https://doi.org/10.1080/19401493.2021.1942209.

Wang, A., Li, R. and You, S. (2018) ‘Development of a data driven approach to explore the energy flexibility potential of building clusters’, *Applied Energy*, 232, pp. 89–100. Available at: https://doi.org/10.1016/j.apenergy.2018.09.187.

Zhu, J. *et al.* (2021) ‘The influence of group-level factors on individual energy-saving behaviors in a shared space: The case of shared residences’, *Journal of Cleaner Production*, 311, p. 127560. Available at: https://doi.org/10.1016/j.jclepro.2021.127560.

Zou, P.X.W. *et al.* (2018) ‘A mixed methods design for building occupants’ energy behavior research’, *Energy and Buildings*, 166, pp. 239–249. Available at: https://doi.org/10.1016/j.enbuild.2018.01.068.

Appendix

Read-only link to ‘Probono carbon footprint behaviours’ Google Sheet, containing the complete dataset reviewed in this document https://docs.google.com/spreadsheets/d/16NOaYpLObkLQ5JH5tK73jZqPRs7t2URpFed0AmP_HBo/edit?usp=sharing